1992

Robot interface in a flexible manufacturing cell

Joäao Paulo Moreira Gonðcalves
Lehigh University

AUTHOR:

Goncalves, Joao Paulo

TITLE:

Robot Interface in a Flexible Manufacturing Cell

DATE: October 11, 1992

ROBOT INTERFACE

IN A

FLEXIBLE MANUFACTURING CELL

by

João Paulo Moreira Gonçalves

A Thesis

Presented to the Graduate and Research Committee

of Lehigh University

in Candidacy for the Degree of

Master of Science

in

Manufacturing Systems Engineering

Lehigh University

July, 1992

CERTIFICATE OF APPROVAL

This thesis is accepted and approved in partial fulfillment of the requirements for the Master of Science.

July 29th, 1992
Date

Dr. Gregory L. Tonkay
Thesis Advisor

Dr. Keith M. Gardiner
Director, MSE program

Dr. David B. Williams
Chairman, Materials Science and Engineering Department

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to those individuals and organizations who made my studies at Lehigh University and the completion of this research work possible. Specifically, I would like to thank my former professors from Faculdade de Engenharia da Universidade do Porto, Prof. Paulo T. Castro and Prof. Rui C. Guimarães, Dr. Keith M. Gardiner, director of MSE program, and staff, the coordinators of the AMNIOP program, Fundação Luso-Americana para o Desenvolvimento, and the organization that funded these studies, Junta Nacional de Investigação Científica e Tecnológica.

I would like to extend special thanks to Dr. Gregory L. Tonkay for providing his guidance and assistance. Such assistance was a large contribution to the terrific learning experience during this period. I thank him for his interest in this work as well.

I also owe special thanks to Mr. Gilbert Zambelli, who helped me with the extensive mechanical work involved in this project, and to Mr. Edwin Force II, who helped me with the electrical work and much more. Without their contribution it would not have been possible to complete this work.

Lastly, many thanks to my friends, who were there to offer me encouragement and support during this challenging and rewarding period. Especially, I would like to express my warmest thanks to my friend Cynthia for everything including the help in the preparation of this paper.

TABLE OF CONTENTS

LIST OF FIGURES

ABSTRACT

Manufacturing companies are focusing on more flexible strategies in order to respond to the demands of the present markets. One of the possible improvements in that direction, and a possible rewarding capital investment for a company, is the use of flexible manufacturing cells. These cells are workstations that via computer control can quickly modify the sequence and the type of operations. This capability increases the flexibility to manufacture different products or products with different properties. These cells can also be part of a more complex flexible manufacturing system with a central computer control, that manages production scheduling and other items.

This project consisted of the design of the interfaces between a robot, a CNC turning center and a cart-on-track system in order to attain a flexible manufacturing cell in the Manufacturing Technology Laboratory at Lehigh University. The result is a cell that has a CNC turning center as the production unit and a robot that grasps the workpieces from a cart stopped at the cell station, and loads them into the turning center. The workpieces are subjected to cutting operations accomplished under control of a NC program. The flexibility of the cell is obtained by the use of different NC programs that allow various products to be manufactured.

CHAPTER 1

PROBLEM DEFINITION

1.1 Flexible Manufacturing Cell

A flexible manufacturing system (FMS) has a number of potential definitions. The following however, seems to be the more commonly used definition of a FMS (Groover, 1987 and Young and Greene, 1986) : "A group of processing stations (predominantly CNC machine tools), interconnected by means of an automated material handling and storage system, and controlled by an integrated computer system." An important component of FMS is its capability to simultaneously process a variety of different types of parts that all belong to similar families, each part at a different workstation.

It is just as difficult to find a precise definition for a flexible manufacturing cell as it is for a FMS. Generally, a cell can be defined as a group of machines that can be either manually operated or automated. A cell need not necessarily have automated material handling or computer control. For Green (1986) the distinction between a FMS and a FMC is the degree of control employed:

> The FMC can take a number of configurations, but it generally has one or more machine tools with some material-handling device such as a robot. In most cases, the grouping of machines is small and often uses a common pallet or part-fixturing device. The FMC generally has a fixed process, and parts flow sequentially between operations. The cell lacks central computer control with real time routing, load balancing and production scheduling logic. The flexible manufacturing system (FMS) includes at least three elements: a number of workstations, an

automated material-handling system, and system supervisory control. The FMS is typically designed to run for long periods with little or no operator attention. Central computer control over real-time routing, load balancing, and production scheduling distinguish FMS from FMC.

In terms of production, a FMS lies somewhere between high-production transfer lines and low-production NC machines. A transfer line is the most efficient method to achieve high volumes and output rates. However, it is limited to a product or family of products. If the product undergoes substantial changes this system may be rendered obsolete. On the other hand, stand-alone NC machines do not produce at a high output rate, but do allow for flexibility in product design changes. FMS is the potential solution for mid-volume production. Unlike a transfer line, a FMS can be used to run a variety of product configurations therefore giving it flexibility. Compared to stand-alone NC machines, FMS not only has a higher output rate, it also has the advantage of accepting an intermix of products on the system. This intermixing of products on the system will reduce the work-in-process and final inventories by setting the output rate of each product at its corresponding demand rate. Other benefits of a FMS are pointed out by Talavage and Hannan (1988). They are: increased machine utilization and productivity of working capital; reduction of labor costs, number of machine tools, lead times, and setup costs; more consistent product quality and less floor space.

Although a FMS has associated with it a long list of possible benefits, there are also several problems that include technical, cost and justification problems

(O'Grady, 1989). As a result, industries of all sizes appear to be investing in cells. Often the only way small companies can introduce FMS concepts is to build islands of automation which can later be integrated into a system.

As it was stated before, a FMC consists of one or more machine tools and a material-handling device. The latter can be a specialized material-handling device but is usually a robot. A cell that has one or more robots is commonly called a robot workcell. This kind of cell can be organized into various layouts (Groover, Weiss, Nagel and Odrey, 1986). The three basic types of layouts are: robot centered cell, in-line robot cell, and mobile robot cell.

In the first one, the equipment is located around the robot, usually forming a partial circle. In the second one, the robot is located along a moving conveyor or other such handling system. As the product passes by on the conveyor, a task is performed on it by the robot. In the last type of layout, the robot has the capability of moving and reaching each one of the pieces of equipment within the cell.

This project consists of designing and implementing a flexible manufacturing cell which is being built in the Manufacturing Technology Laboratory of the Department of Industrial Engineering at Lehigh University. In this laboratory there is an automated storage/retrieval system (AS/RS) connected with a material-handling system that is a cart-on-track conveyor. Parts can be retrieved from the AS/RS and placed on a cart, or vice-versa. Along this cart-on-track conveyor there are several designated positions to place workstations at which the cart is able to stop. This permits the loading and unloading of parts that are transported on the cart. The parts arriving at a workstation come from the AS/RS or from another workstation. They are processed and then sent back to the AS/RS or to another workstation. The cell developed in this project is placed at one of the workstation positions.

The cell consists of a numerically controlled turning center and a robot. The function of the robot is to load the workpiece into the machine and to remove the finished product when it is completed. The CNC turning center can perform a number of operations on the workpiece to produce the finished product. The NC program previously loaded into the turning center generates the tasks to be executed automatically.

The work accomplished in this project was the design and implementation of the interfaces between the robot, the CNC turning center and the cart-on-track conveyor system. It is this work that produces a flexible cell.

1.2 Description of Cell Components

The primary pieces of equipment related to the cell were already available in the laboratory and include the CNC turning center, the robot, and the cart-on-track conveyor system. The following is a brief description of the components.

CNC Turning Center

A turning center is a machine tool that is best suited to machine parts with a revolutionary shape. The machine contains a spindle with rotational movements at the end of which a workpiece is mounted. The cutting tool has a linear or arc movement that when combined with the rotation of the workpiece produces the desired cutting operation.

The turning center used in this project was manufactured by EMCO MAIER Corporation of Austria. It is the model Emcoturn 120P CNC. It is a slant bed lathe with maximum power on the main spindle drive of 5.5 hp. At the end of the main drive there can be attached a pneumatic three-jaw chuck or a pneumatic 5C collet. Either one of these devices is used to hold the workpiece in place. The tools are fixed in a turret that can move in a plane using two axes and is able to hold eight tools simultaneously. The turret has an automatic rotational movement so that the desired tool can be placed in working position. The dimensions of this turning center allow the production of workpieces up to 3" x 5".

The control is an Emcotronic T1. This is a CNC two-axis contouring controller which is capable of linear and circular interpolation. The controller possesses various modes of operation that permit the turning center to be operated in a manual or automatic mode. The automatic mode is selected to execute a pre-programmed NC program. An edit mode allows for the creation or change of a NC program. The input of a program is done via keyboard or via computer interfaces. Figure 1-1 shows the turning center and its controller.

Robot

The definition of an industrial robot by the Robotics Industries Association is: " a reprogrammable, multifunctional manipulator designed to move materials, parts, tools, or special devices through variable programmed motions for the performance of a variety of tasks."

Robots are available in a wide variety of shapes and physical configurations. The robot used in this project has a jointed-arm configuration which is similar to that of the human arm (see figure 1-2). It consists of two straight elements mounted on a vertical pedestal and connected by two rotary joints. The straight components are the equivalent of the human forearm and upper arm. The joints correspond to the shoulder and elbow. At the end of the forearm a wrist is attached, which provides various additional rotary joints.

The robot available is a Unimate Puma 560 from Unimation Inc. It consists of six revolute axes, each one driven by electric DC servomotors. The axes of rotation are shown in figure 1-3.

In addition to the robot arm, the robot system contains a controller, a teach pendant, a terminal, software and peripherals (Puma Robot, 1982).

The controller is the main component of the electrical system. The signals to and from the robot pass through the controller. The latter uses these signals to perform real-time calculations that control arm movement and position. The system software that controls the arm is called VAL. This is a high level language. The VAL programming language consists of a full set of English language instructions for teaching and editing. The VAL control system can also communicate with other computer based systems such as vision or force sensors (Puma Robot, 1982). The VAL software is stored in the computer memory of the controller. The software interprets the operating instructions for the robot arm. The controller then transmits these instructions to the arm. The controller also receives data about the arm position from incremental encoders and potentiometers in the robot arm. This provides closed loop control of the arm motions. Figure 1-4 is an illustration of the controller's front panel where the operating controls and connections for terminal, teach pendant, floppy disk, and accessory are located.

The teach pendant is used to position the robot arm by manipulating the joints using a keypad. It can be used to manually direct the movements of the arm through each step of the task. These steps are recorded and then stored in the computer memory (Puma Robot,1982).

The terminal consists of a keyboard combined with a video (CRT). It is used to teach and edit programs and also to communicate with the control system.

An optional peripheral is a floppy disk unit. It allows for the permanent storage of programs. This is not possible in the controller memory.

The following are other characteristics of the Puma 560:

- Position repeatability: this is concerned with its ability to position the wrist or an end effector attached to the wrist at a point in space that had previously been taught to the robot (Groover, Weiss, Nagel and Odrey, 1986). For this robot the position repeatability is 0.1 mm (0.004 inches).

- Static force: the maximum load that can be applied at the wrist tip is 58 N (13 lb).

- Work volume: this is the space within which the robot can manipulate its wrist end. The size and shape of each work volume is influenced by the dimensions of the arm elements and by the limits of its joint movements. The work volume of the Puma 560 is shown in figure 1-5

Cart-on-track

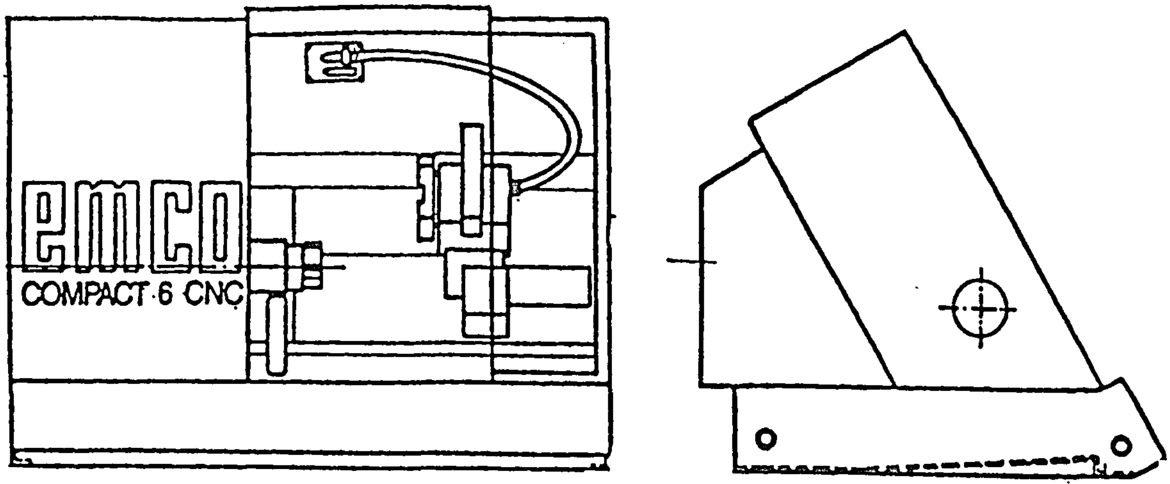
Conveyors are a type of automated material handling system. A cart-on-track is a conveyor system that consists of individual carts that ride on a two-railed track. A frame supports the track a few feet above floor level. The carts are powered by means of a rotating tube that runs between the two rails. A drive wheel is attached to the bottom of the cart and contacts the rotating tube. If the contact occurs at an angle, the cart is moved forward. As compared to other types of conveyors, this system can achieve relatively high position accuracies. Figure 1-6 shows the layout of the cart-on-track system in the laboratory.

The cart-on-track conveyor system available at the laboratory is controlled by a Programmable Logic Controller (PLC). This controller has a number of input/output ports that can be augmented by the addition of modules. The input signals usually come from switches, limit switches or other kinds of sensors. These signals convey the state of the cart-on-track or other such controlled devices. A program in the controller monitors the input signals and sends out appropriate commands that control the sequence of outputs on the device. The PLC is programmed using ladder logic diagrams. These are the most commonly used diagrams for describing nonelectronic control circuits (Webb, 1992).

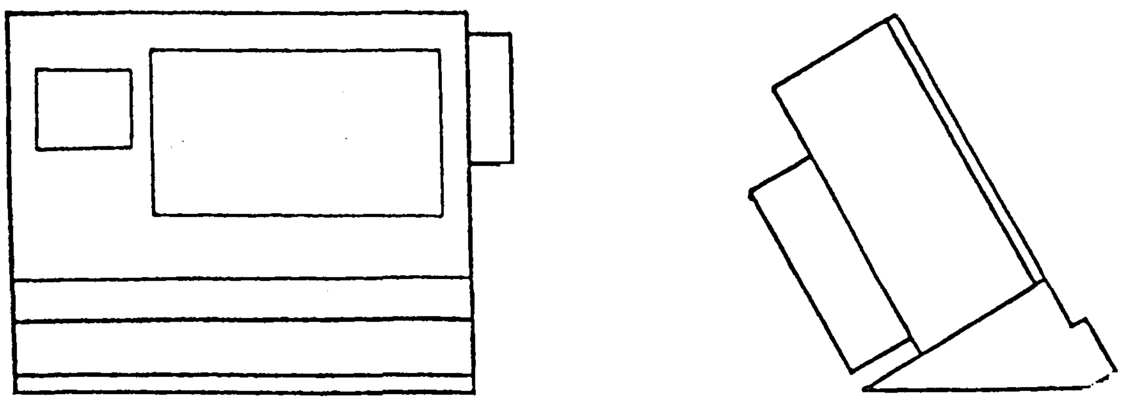
1.3 Constraints

The CNC turning center, the robot, and the cart-on-track, and its controller were already located in the laboratory. The purpose of this project was to develop a cell with these available components. If the development of this cell had included the selection of the robot, other robots would be more appropriate for this task. Given a jointed-arm robot, the size of the Puma 560 does not provide flexibility to load or unload parts of various shapes and sizes.

Besides the restriction of having to use the existing components, the layout design is limited as well. The CNC turning center is used to teach the Industrial Engineering students the principles of CNC programming. Students have to learn how to use and program this turning center. They are required to produce a simple machined part by manually preparing a NC program and executing it. To allow manual operation of the CNC turning center, the cell layout had to be carefully designed. Space had to be available in front of the machine so that a person could stand and have access to the spindle as well as the controller.



Emcoturn 120P CNC



Emcotronic T1

Figure 1-1: Emcoturn 120P CNC and Emcotronic T1 (from Emco, 1986)

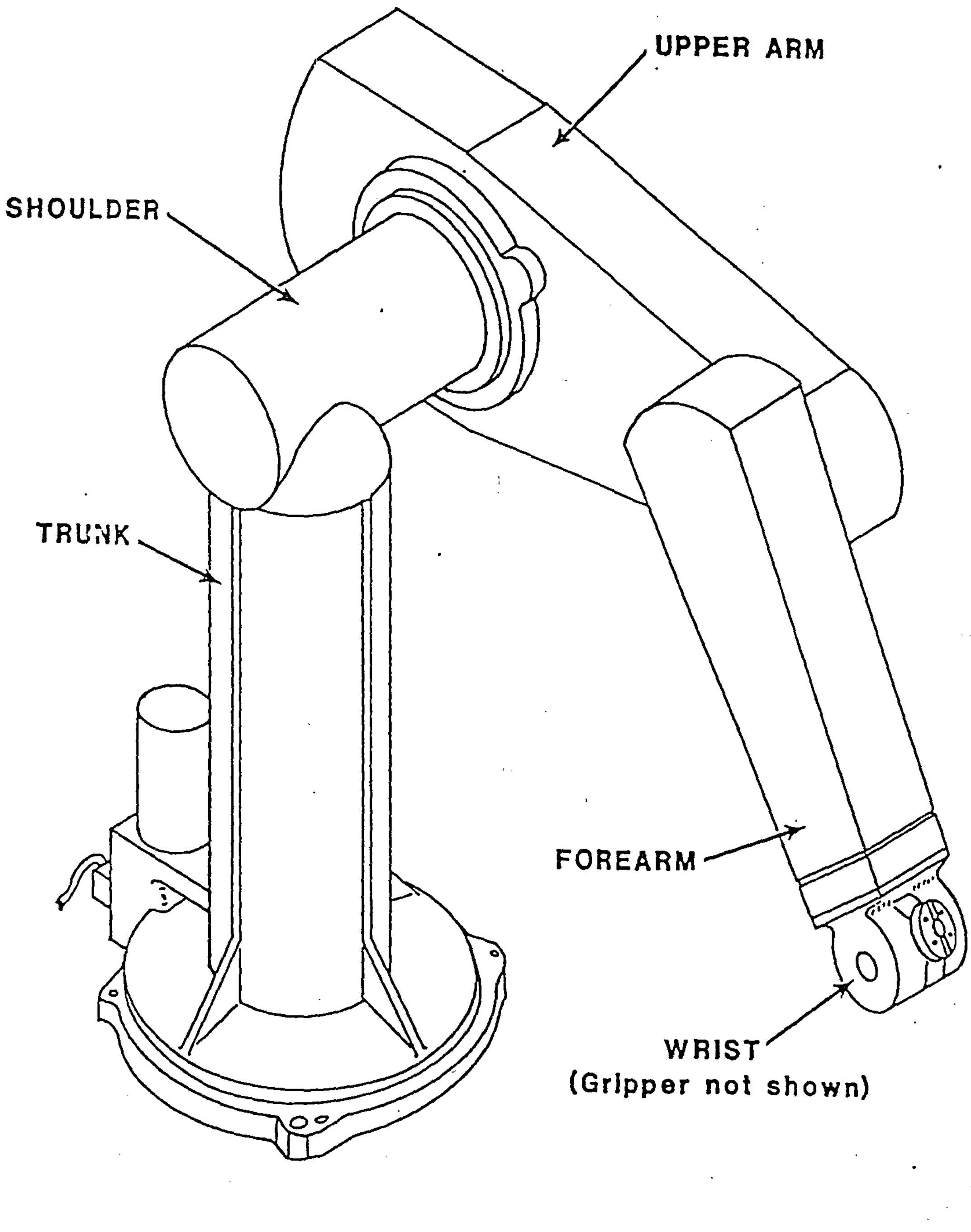


Figure 1-2: Jointed-Arm Robot (from Puma Robot,1982)

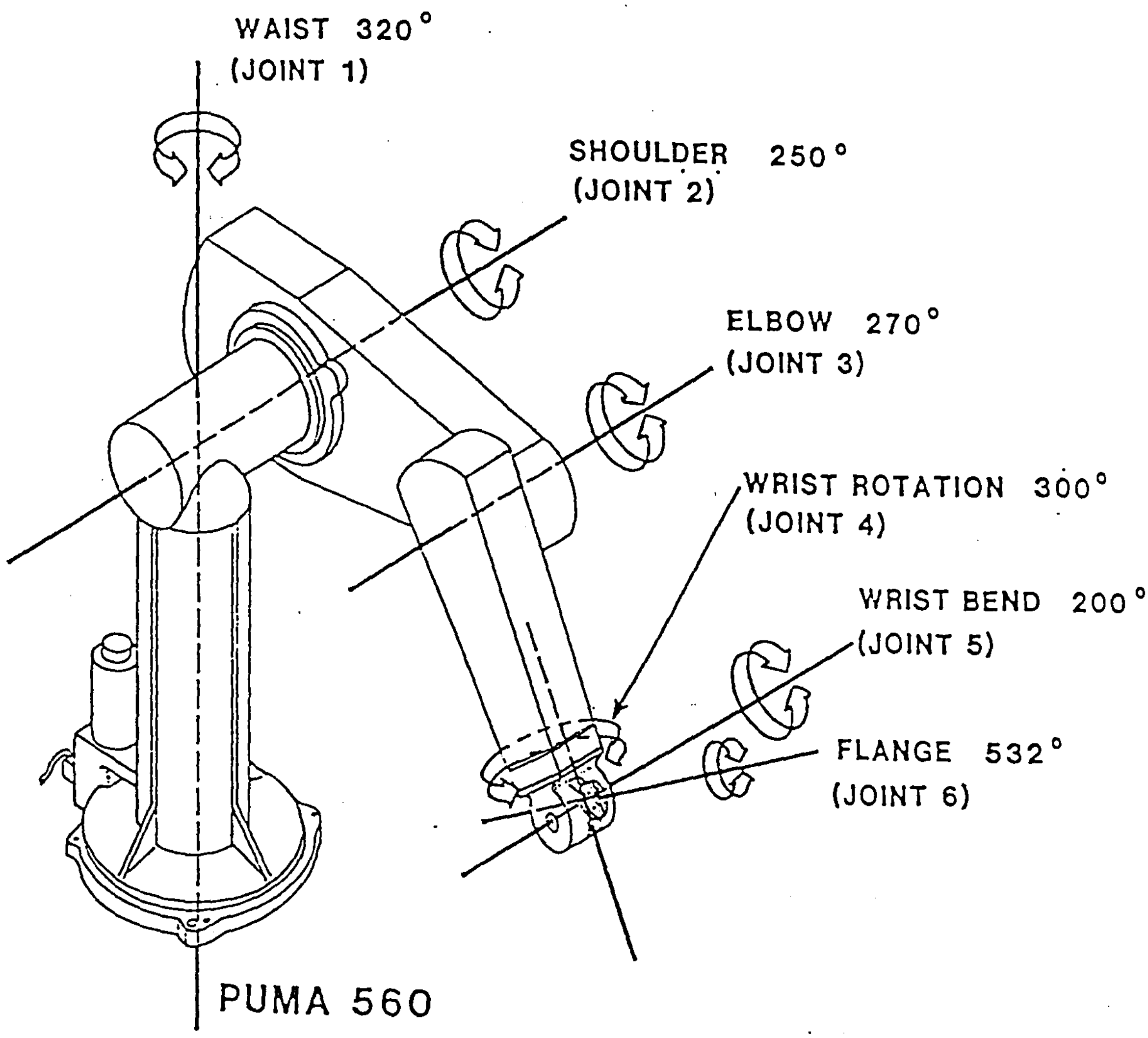


Figure 1-3: Robot Unimate Puma 560 (from Puma Robot, 1982)

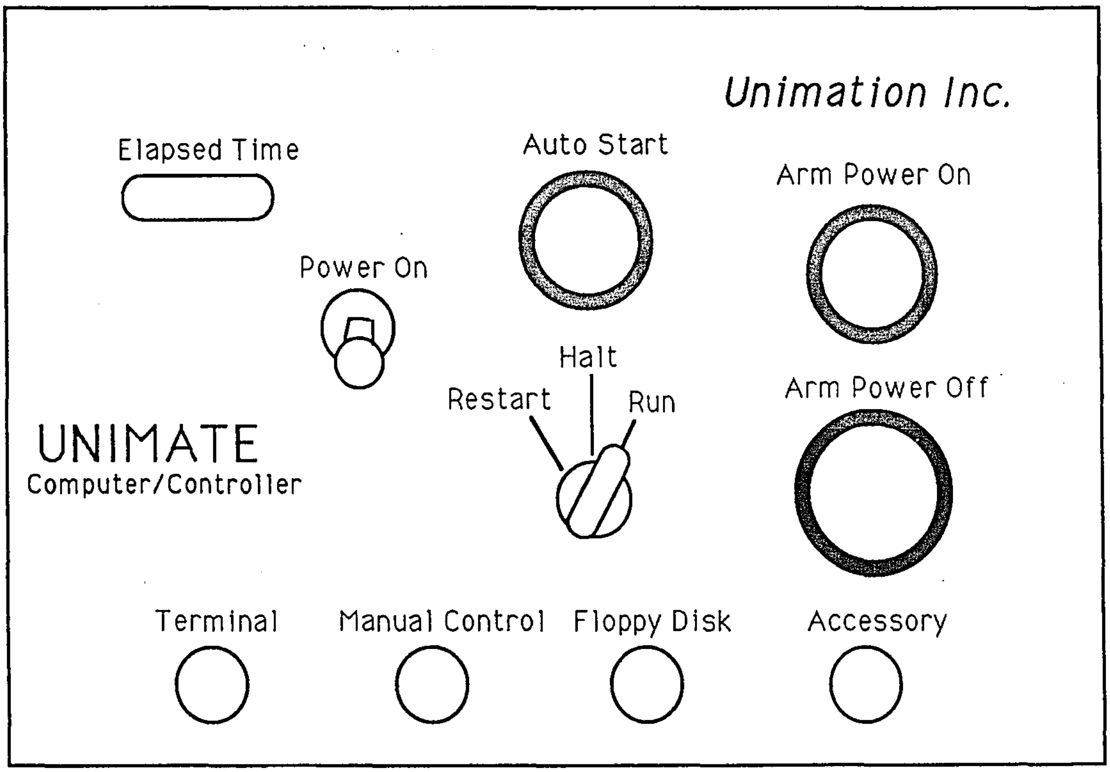


Figure 1-4: Unimate Robot Controller

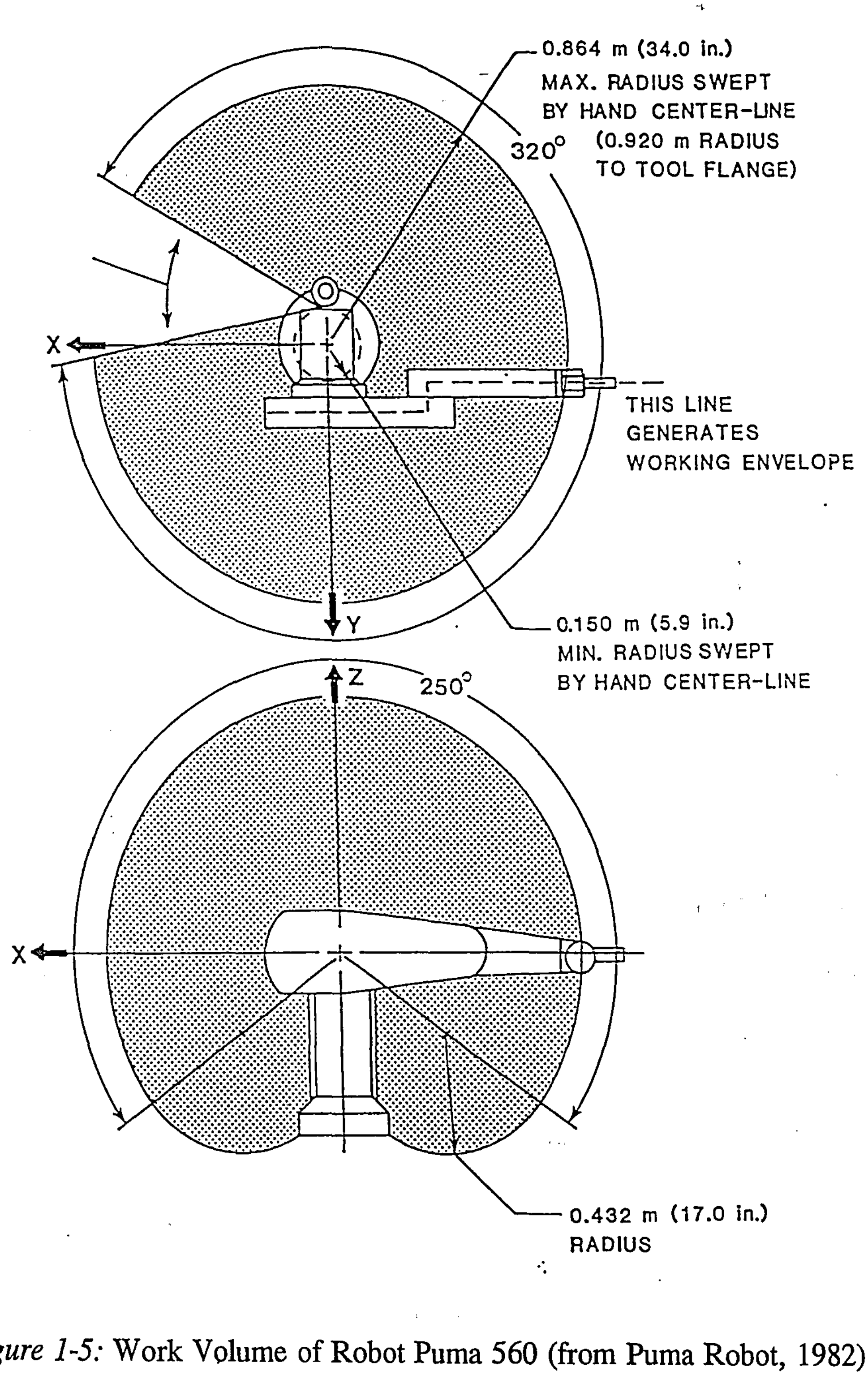


Figure 1-5: Work Volume of Robot Puma 560 (from Puma Robot, 1982)

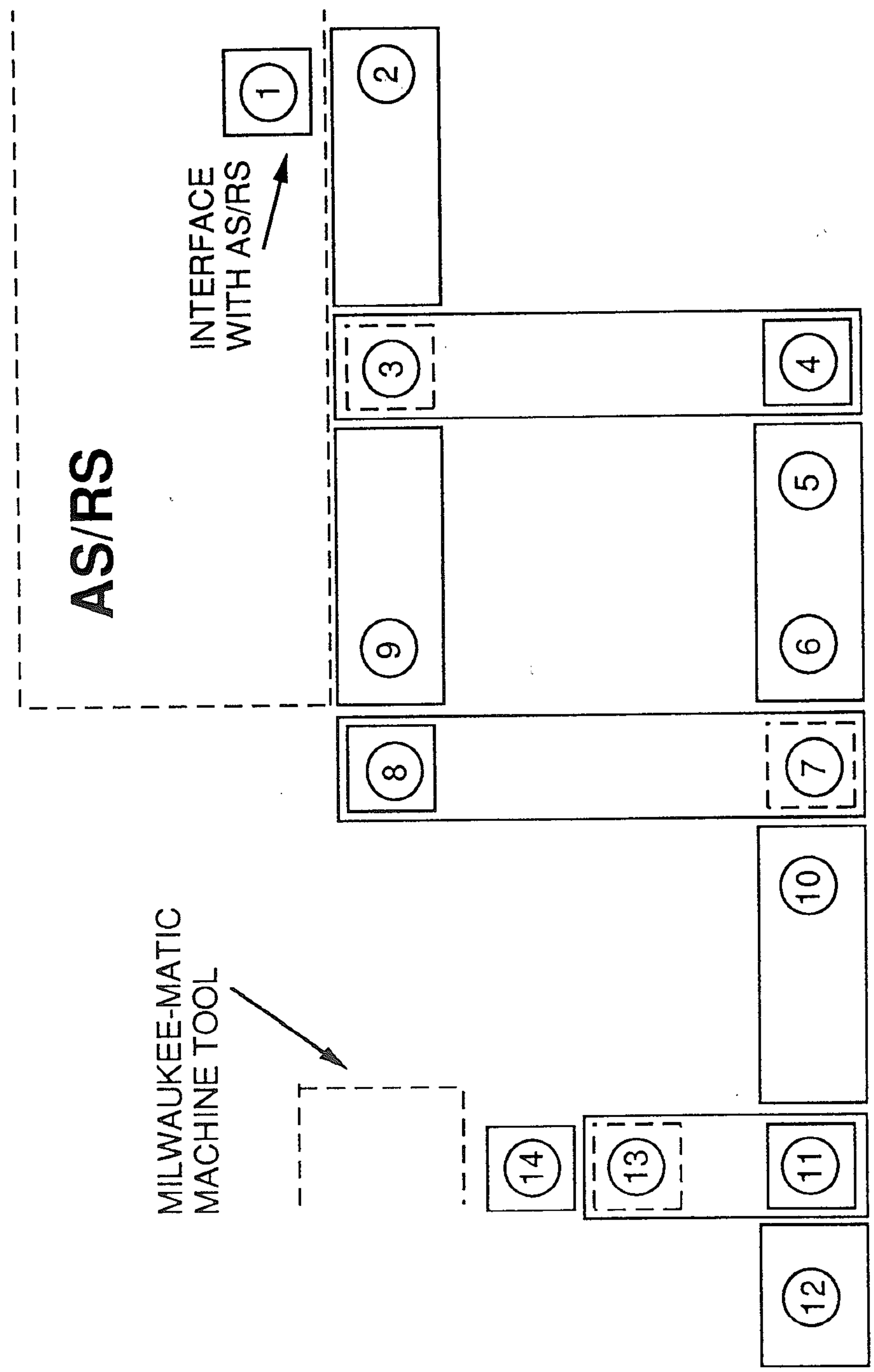


Figure 1-6: Cart-on-Track System Layout

CHAPTER 2

DEVELOPMENT OF ROBOT INTERFACE

2.1 Description of Proposed Cycle

As previously stated, the cell consists of a CNC turning center and a robot. The cell was placed by one of the locations on the cart-on-track system where it is possible to stop a cart. A cycle of the cell starts upon the arrival of a cart at that location. The robot arm moves to grasp a workpiece from the cart. The wrist has an end effector attached to it that is designed to properly hold the type of workpart to be processed in the cell. As the end effector reaches the first workpiece, a signal is sent that commands the end effector to grasp the part. The robot takes the part from the cart and brings it to the turning center. The latter has both the collet and the door open, and is ready to receive the part. The robot arm places the part inside the collet, sets it free and returns to its ready position. The ready position is the configuration that the arm takes when it is waiting for the turning center to finish.

When the robot reaches the ready position, the door closes and the turning center is ready to start its cycle. The cycle begins when the workpiece is adjusted to its final position from the position in which the robot left it. It is an operation accomplished by the turning center with help of a specialized tool. After the collet tightens around the workpiece, the cutting operations begin. This machine cycle is the execution of a previously edited NC program. The program delineates the sequencing of operations to be executed on the workpiece in order to achieve the final product.

In this example, the processing cycle ends with a cutting operation where the finished piece is separated from the part that remains in the collet. The former drops inside the machine and can than be removed when the cell operations stop. The latter is often scrap, but might happen to have some utility. In either case, that part has to be removed from the collet. After the collet is loosened and the door is opened, the robot arm moves inside the NC turning center and its end effector grasps the spare piece of material. The robot arm moves away from the turning center and places the end effector above a bucket situated by the machine. At this position the end effector releases the piece into the bucket. At this time a cycle is complete, and another one may begin. The robot arm moves its end effector to the cart and grasps the second part.

This cycle is repeated until the workpieces existing on the cart are all processed. When this happens, the robot arm returns and stops at its ready position. The cart is released and travels to its appointed station.

2.2 Component Interface Signals

As it is evident from the previous description of the cell cycle, the majority of the activities in a cell occur sequentially. Simultaneous activities can also occur but with a single machine tool they are less common. Coordination of the various activities is accomplished by a device called a cell controller. Either a robot controller or a high level control device, such as a programmable logic controller, is used as a cell controller. The robot controller usually has a limited input/output capability that permits interfacing with other equipment in the cell.

Thomas (1983) suggested that the functions performed by the workcell controller can be divided into three categories: sequence control, operator interface, and safety monitoring. Sequence control is the main function of the workcell controller for regular operation of the cell. It includes several kinds of control functions:

- Control of the sequence of activities in the cell.
- Control of simultaneous activities.
- Making decisions to proceed with the work cycle based on events that occur in the cell.
- Making decisions to stop or delay the work cycle based on events that occur in the cell.

Operator interface provides the possibility for human operators to interact with the operation of the cell. There are several situations where this is required. For instance, human intervention is necessary for making an emergency stop of the cell when some problem is detected. Besides this capability, the workcell controller should also be able to monitor its own operation for unsafe or potentially unsafe conditions in the cell.

The main elements in a cell (in this case: the robot, the CNC turning center, and the cart-on-track system) usually work as separate units. For instance, the CNC turning center operates under numerical control to perform its automatic cycle. The function of the cell controller is to make sure that the various activities begin at the required times. To perform this function, the cell controller has to be able to communicate with the various elements in the cell. Signals must be sent by the cell controller to the components of the cell, and other signals must be received from those components. Groover, Weiss, Nagel, and Odrey (1986) call these signals interlocks. They define an interlock as a method of preventing the work cycle sequence from continuing unless a certain condition or set of conditions are satisfied. Their use provides a synchronization and pacing of the activities in the cell. They allow for variations in the times taken to complete certain operations in a cycle by prohibiting operations from starting prematurely. This helps prevent damage to the cell components. An example of an interlock used in this project, is one that makes certain that the cart arrives before the cell cycle begins.

Interlocks can be divided into two categories: output interlocks and input interlocks. An output interlock is a signal sent from the cell controller to one of the components in the cell. It is generated when specific conditions are verified. These conditions are usually determined by means of input interlocks.

An input interlock is the signal sent from an element of the cell to the cell controller. It is used to indicate that a certain condition has been met and that the programmed cycle sequence can continue.

In this cell, the robot controller was chosen to perform the coordination of the various activities. This controller possesses the necessary characteristics to coordinate the activities of this cell. Because those activities occur sequentially the task of the controller is less complicated. Also, the input/output capabilities that the robot controller has, are enough for the needs of the cell.

In following the steps of a cell cycle, the interface signals needed to allow the robot controller to coordinate the various activities can be identified. As described, a cycle begins when a cart arrives at the designated cell station. At this point the PLC, which is the device that controls the cart-on-track, must send a signal to the cell controller indicating that a cart has arrived. Before the controller commands the robot to take a part from the pallet and load it into the turning center, it must prepare the CNC turning center to receive that part.

Since the CNC turning center door was manually operated at the beginning of the project, a device that allows for the automatic opening and closing of the door had to be installed. The robot controller receives a signal from one limit switch, that indicates the door is closed, and a signal from another, that indicates the door is opened. The limit switch that indicates a closed door was already incorporated in the machine. The other one, indicating that the door is completely open, had to be installed.

After receiving the signal from the PLC corresponding to the arrival of the cart, the robot controller sends a signal to open the door. It will then wait for the signal from the limit switch that indicates that the door is completely open. Upon the arrival of this signal, the robot arm can move, pick up a part from the pallet, and place it in the collet of the turning center. The system that opens and closes the gripper is already built into the robot arm and is actuated by signals generated by software commands.

After the robot arm has returned to its ready position a signal has to be sent to close the door. This signal can be the inverse of the one sent to open the door. This means that the same interface is able to produce the opening and closing of the machine door. The controller will then be waiting for a signal coming from a switch, indicating that the door is completely closed.

When that signal arrives, the controller sends yet another signal that starts the operations of the CNC turning center. The turning center executes the NC program which produces a finished part. When the cycle finishes, the machine tool sends a signal to the robot controller. The robot controller initiates the opening of the turning center's door via the previously described signal. When it receives confirmation that the door is completely open, it instructs the robot arm to pick up the excess material remaining in the collet. The removal of that material terminates the cycle for production of that part. The robot is now ready to move, pick up another part and place it in the collet of the turning center.

The sequence described above is repeated as many times as the number of workpieces contained on the pallet requires. When the last piece is completed and the robot arm returns to the ready position, the cart moves on, via a signal from the controller to the PLC which indicates a finished cycle. At this point, another cart full of workpieces can replace the previous one.

The signals described above are an essential component of the work cell. They are summarized as:

- Output interlocks:
  - to the CNC turning center
    . Open/close door.
    . Start cycle.
  - to the PLC
    . Cell cycle completed. Cart can be removed.
- Input interlocks:
  - from the CNC turning center
    . Door is completely closed.
    . Door is completely opened.
    . End of cycle.
  - from the PLC
    . Cart has arrived. Cell operations can begin.

Figure 2-1 represents the signals described above.

2.3 Interface Design Hardware

The robot controller needs an I/O module to interface with other cell components. The I/O module is a rack-mountable module that can receive and act on input signals, or can generate output signals (Puma, 1982). Each I/O module contains eight output and eight input lines. It contains a LED for each input/output signal that lights when power is applied and thus may be used to monitor the state of any signal.

The relays mounted in the I/O module are solid state, optically coupled, and are designed for open collector transfer operation (Puma, 1982). The relays are color-coded for voltage and function. The 24 VDC input relays are white, the 24 VDC output relays are red, the 110 VAC input relays are yellow and the 110 VAC output relays are black. The power that supplies any of the signals used is not generated by the robot controller, but rather by an external power source. Figure 2-2 shows the I/O module used in this project.

As recommended by Thomas (1983) the signals used for interfacing the various components in the cell are the standard 24 VDC and 110 VAC. The signals used to interface the robot controller with the turning center are all 24 VDC and the signals used to interface with the PLC are 110 VAC. The following is a description of the interfaces implemented.

- Output signals from the robot controller

The PLC has input modules that make it easy to interface a signal from any device. Each module has sixteen input lines divided into two groups of eight. In each group the lines are internally connected with a common line that is in turn connected to the neutral line of the 110 VAC power supply. As shown in figure 2-3 the circuit that was installed consists of a line connecting the output module on the robot controller to the hot line of the 110 VAC power supply, and another line extending to one of the input lines of the PLC.

There are two output signals connecting the robot controller to the machine tool. The signal used to open/close the front door of the machine tool is directed to a pneumatic valve that is controlled electrically. This valve controls the movement of a pneumatic cylinder that opens and closes the door. The signal is powered by an external power supply of 24 VDC. The circuit that is installed has the power supply connected in series with the output relay and the pneumatic valve (see figure 2-4). The signal that is used to start a cycle of the CNC turning center replaces a button existing on the side of the machine. This button was used to start a cycle of the machine in automatic mode. The button was disconnected and in its place the robot output relay was connected (see figure 2-5).

- Input signals to the robot controller

The output modules of the PLC are divided into two groups of eight output lines each. In each group every line is connected internally to a common line that is in turn connected to the hot line of the 110 VAC power. The circuit interfacing the output line of the PLC with the input module at the robot controller is represented in figure 2-6. One of the lines of the circuit is connected with the neutral and the other with the output line of the PLC.

There are three input signals coming from the machine tool. Two of them are coming from limit switches, one indicating that the door is completely open and another indicating the door is closed. For both, the external power supply of 24 VDC is used, and in both cases the circuit implemented consists of the power supply, the limit switch and the input relay (see figure 2-7). The signal that indicates the end of the cycle is not a pre-defined signal from the machine output signal that indicates the status of the machine. The potential for locating this signal exists. But because the schematic of the wiring in the machine is not available, it could not be located. To solve this problem a signal coming from a valve that controls the opening and closing of the collet was used. It is known that a workpiece during a machining cycle has to be held in place by the collet. When the cycle finishes, the collet is open so that the workpiece can be removed. This last operation of the machine cycle is controlled by the NC program. As the solution, the signal sent to change the state of the valve that controls the opening and closing of the collet was sent to the robot controller. Thus, a circuit was installed to connect the machine tool valve to the input relay on the robot controller (see figure 2-8). The voltage used to power the valve and the relay is 24 VDC.

2.4 Discussion of Work Accomplished

Layout design was the first step taken in the process of building the robot workcell. Following the layout came the design of a gripper, the design of a system that opens the machine door automatically, modifications in the collet, design of a pallet, electrical connections, computer program development, and NC program development.

Layout: The layout design had to remain within the boundaries set by the constraints that were defined in the first chapter. That is, the robot and the CNC turning center had to be positioned in such a way that manual operation of the turning center was still possible. In addition to this, the robot arm had to be able to reach the position that would allow it to load a workpiece into the collet.

Station 12 of the cart-on-track system (see figure 1-6) was defined as the station to load parts into the cell. By taking into consideration the work volume of the robot and by repositioning the turning center and robot, the best possible positioning between the devices was determined. That layout can be observed in figure 2-9. The distance between the robot and station 12 also had to be selected such that the robot could reach every workpiece in the pallet on the cart.

After looking at the possible layouts of the cell, figure 2-10 was determined to be the best. Here, the machine is readily accessible, and there is enough space to work within. The robot controller and the terminal are positioned out of the work volume of the robot in such a way that it is easy to keep in view the entire cell.

Gripper design: An end effector is a device that is attached to the wrist of the robot arm and enables the general-purpose robot to perform a specific task (Groover, Weiss, Nagel, and Odrey, 1986). An end effector is a special-purpose tool for a robot that is specifically designed for a particular task that needs to be executed. It is obtained either by designing and fabricating the device from scratch, or by purchasing a commercially available device and adapting it to the application.

End effectors can be found in a wide variety of types. These can be divided into two major groups: grippers and tools. Grippers are used to grasp and hold objects that are going to be moved by the robot. Tools, as the name indicates, are end effectors used to perform some work on a part. Spray painting and arc welding are examples of applications where tools are used as end effectors.

A gripper can hold a part by mechanical means or by other physical principles such as suction or magnetism. In a mechanical gripper fingers are actuated by means of a mechanism that allows the fingers to grasp an object. The fingers are either attached to the mechanism or are part of it. The ones that are attached can be detached and either replaced, if the part has worn out, or interchanged if another function is desired.

The mechanism that closes the fingers exerts sufficient force in order to secure the piece. This power is supplied from the robot and can be either pneumatic, electrical, mechanical or hydraulic. The Puma 560 is equipped with a pneumatic system that is actuated electrically by the robot controller.

To hold a part firmly in the gripper, one can use two methods. The first one employs a design in which the contacting surfaces of the fingers have the approximate shape of the part it is to hold. The part will be effectively secure between the fingers. The second method simply uses the friction between the fingers and the part. This friction generated when a force is applied by the mechanism has to be able to resist forces such as gravity. This method is less complicated, less expensive and is usually adaptable to a large variety of workparts. Figure 2-11 is an illustration of these methods.

The workings of a gripper can be differentiated by the type of movement that the fingers have. Pivoting movement and linear movement are the options. As can be seen in figure 2-12, in the pivoting movement the fingers rotate about fixed pivot points. In the linear movement, the fingers move parallel to each other.

The construction of the gripper used in this project involved two steps. The first step consisted of designing and building a prototype. The prototype was tested and a new design was developed for the final gripper. The design and execution of the last gripper constitutes the second step.

A gripper mechanism of the linear movement type, that was designed for the Puma 560 was available for modification. The finger of the prototype design consisted of two plates of aluminum bent into a 90° angle at one extremity and of a steel piece with a V shaped wedge attached to the other extremity. The fingers are attached to the gripper mechanism at the 90° end, and the piece is grasped at the other extremity.

A V-block was used at the tip of the finger to grip a part that has a cylindrical shape. Figure 2-13 illustrates the design of this prototype.

Testing proved that the gripper had rigidity problems. Both fingers would bend when a part was grasped. Consequently, subsequent parts were grasped loosely. This problem was resolved in the design of the second gripper. Here, the gap between the fingers when the gripper is closed can be set according to the thickness of the piece to be grasped. This gap can be adjusted by loosening the screws that hold the fingers in place and moving the fingers towards or away from each other in a linear fashion. Also the thickness of the fingers was augmented in order to resist the tendency of bending when a part is being held. Figure 2-14 shows the final design of this gripper.

Design of the automatic opening and closing system of the machine's door: The front door of the machine slides along two rails, one on the front of the machine and the other on the top. A system that automatically opened and closed the door in a linear fashion was designed. The device chosen to generate the linear movement was a pneumatic cylinder. A cylinder with a stroke length equal to the distance of the movement of the door was purchased. This cylinder was placed on the top of the machine, by the rail along which the door slides. A simple mechanical system was used to connect the door to the cylinder. It consists of an aluminum plate attached to the door and to the end of the cylinder rod. Two nuts secure the plate to the cylinder rod. These nuts can be easily removed so that the cylinder can be separated from the door, allowing the door to be manually operated.

A pneumatic circuit was implemented in order to control the movement of the cylinder. This circuit was connected to the line of pressurized air that feeds the turning center. A T element was used to route the pressurized air to the new line. The circuit consists of an air filter, a pressure regulator with a gauge, and a pneumatic valve. The valve has two stable states. In one state the pressure line is connected to one end of the cylinder and the exhaust line to the other. In the other state, the connections are reversed. The valve is controlled electrically by a 24 VDC signal. Figure 2-15 shows a picture of the system.

Modifications in the collet: The collet was modified by machining a chamfer at the face to overcome slight misalignments.

Design of a pallet: The AS/RS and the cart-on-track systems use totes to store and transport parts. For the robot to be able to automatically pick each part up from the cart, each piece has to have a known position and orientation. Because of the gripper design, a vertical orientation of the part was preferred. The pieces also needed to be separated enough from each other to allow the gripper to grasp each part.

A pallet that transports the parts in such a way as to facilitate the task of the robot was needed. This pallet was an adaptation of the totes used to transport all other parts on the cart-on-track system. A wooden plate was placed on the top of the tote creating a plane where parts can be vertically placed. To hold the parts in a vertical position, a block of foam with holes that receive the individual workpieces was fixed to the wooden plate by means of thin aluminum sheets that were screwed into the wooden plate. The individual holes were separated enough to give the gripper access to all parts. Figure 2-16 shows a picture of this pallet.

Electrical connections: The electrical connections needed to interface the robot controller with the turning center and with the PLC were described earlier. Figures 2-3 through 2-8 show those connections.

Computer program development: The control of the cell and of the robot arm movement performed by the robot controller is generated by a computer program. This program was written in VAL, the language used by the Puma 560 controller. The program was written to perform the sequence of operations required to operate this cell. The language permits the control of sequential operations, as is needed in the case of this cell. There is an instruction available that generates a waiting loop in the program if an external signal has not yet arrived. There is also another instruction that generates external signals to control designated devices.

The program written to control the operation of this cell is presented in the appendix. It is not the purpose of this paper to explain in detail every step of the program. Comments are written explaining the functions of each block of the program.

NC program development: The NC program defines the sequence of operations to be performed by the turning center and therefore can generate a variety of final products. For demonstration purposes, a program that was already developed in the laboratory, which produces a complete bolt from the starting cylindrical workpiece was used. Some steps had to be added to the original program that position the workpart before the collet is tightened and the machining operations begin. This positioning is accomplished by a cylindrical stop that is placed in the tool turret, that pushes the workpart to the desired position via a slow linear movement. When the workpart is fully seated, the collet is tightened.

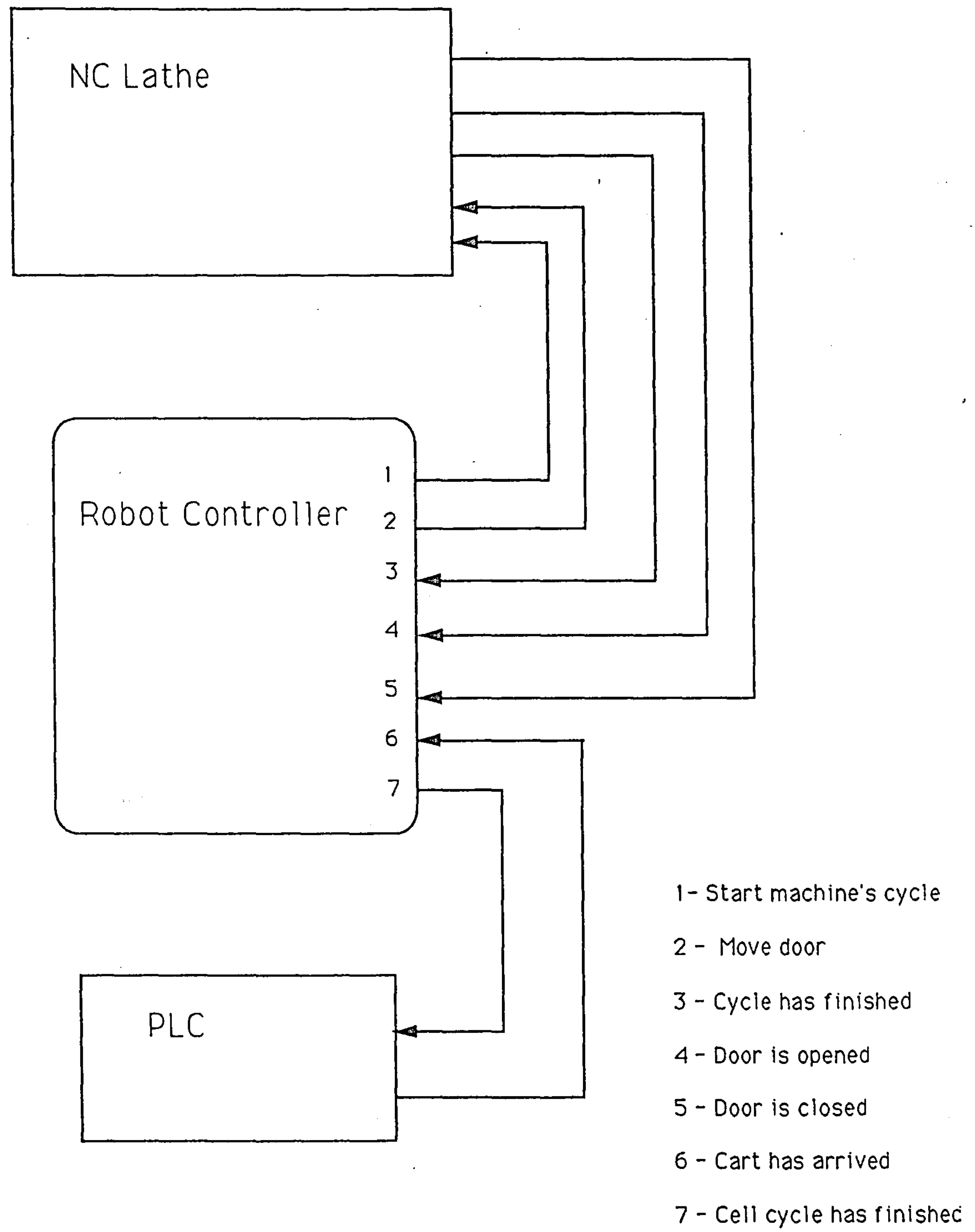


Figure 2-1: Interface Signals

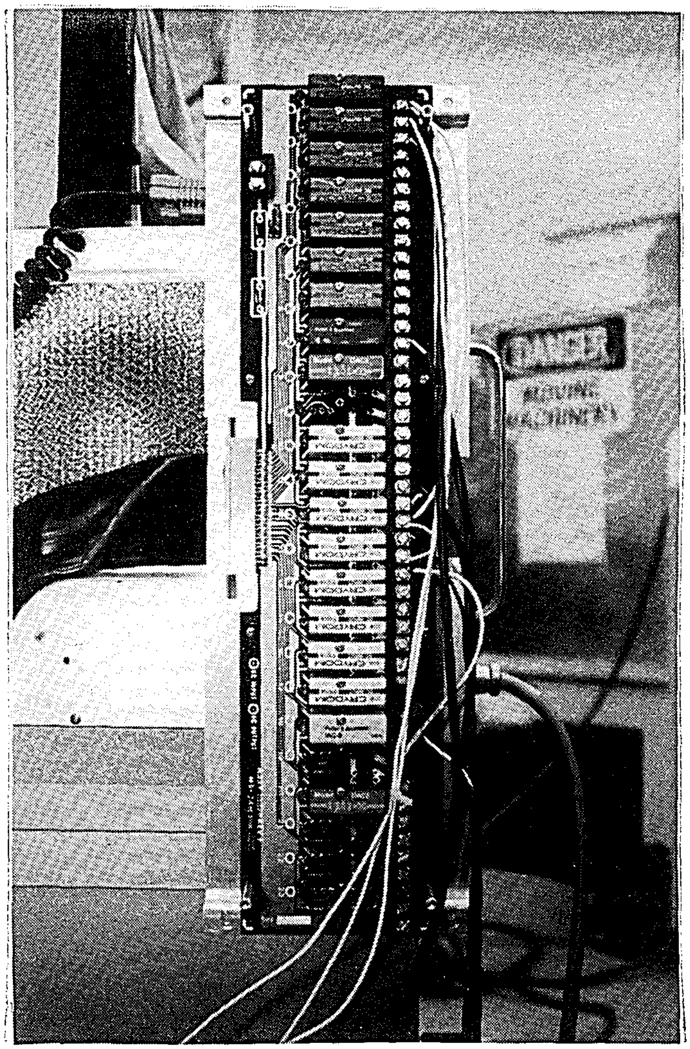


Figure 2-2: I/O Module of Robot Controller

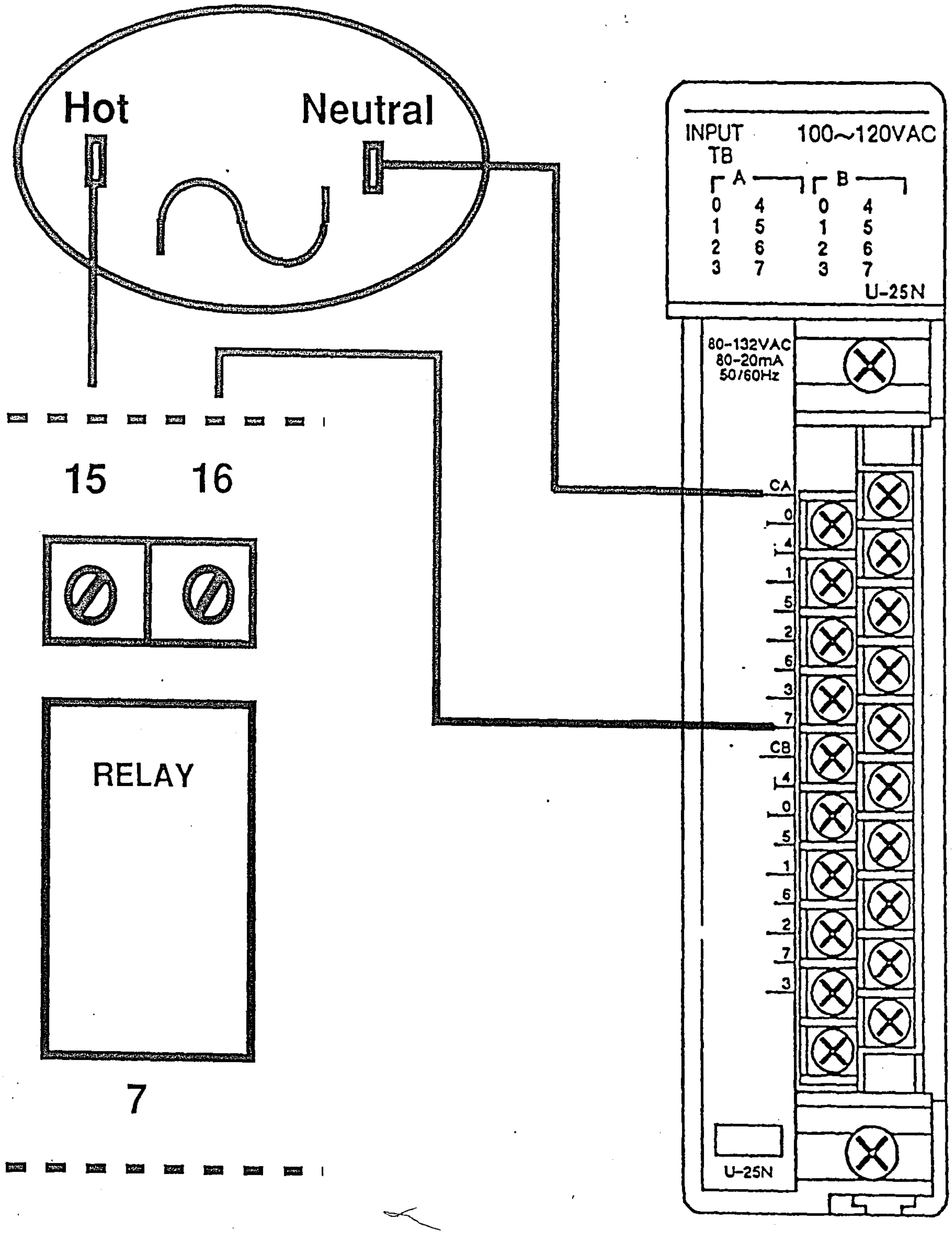


Figure 2-3: Interface Between Output of Robot Controller and Input of PLC

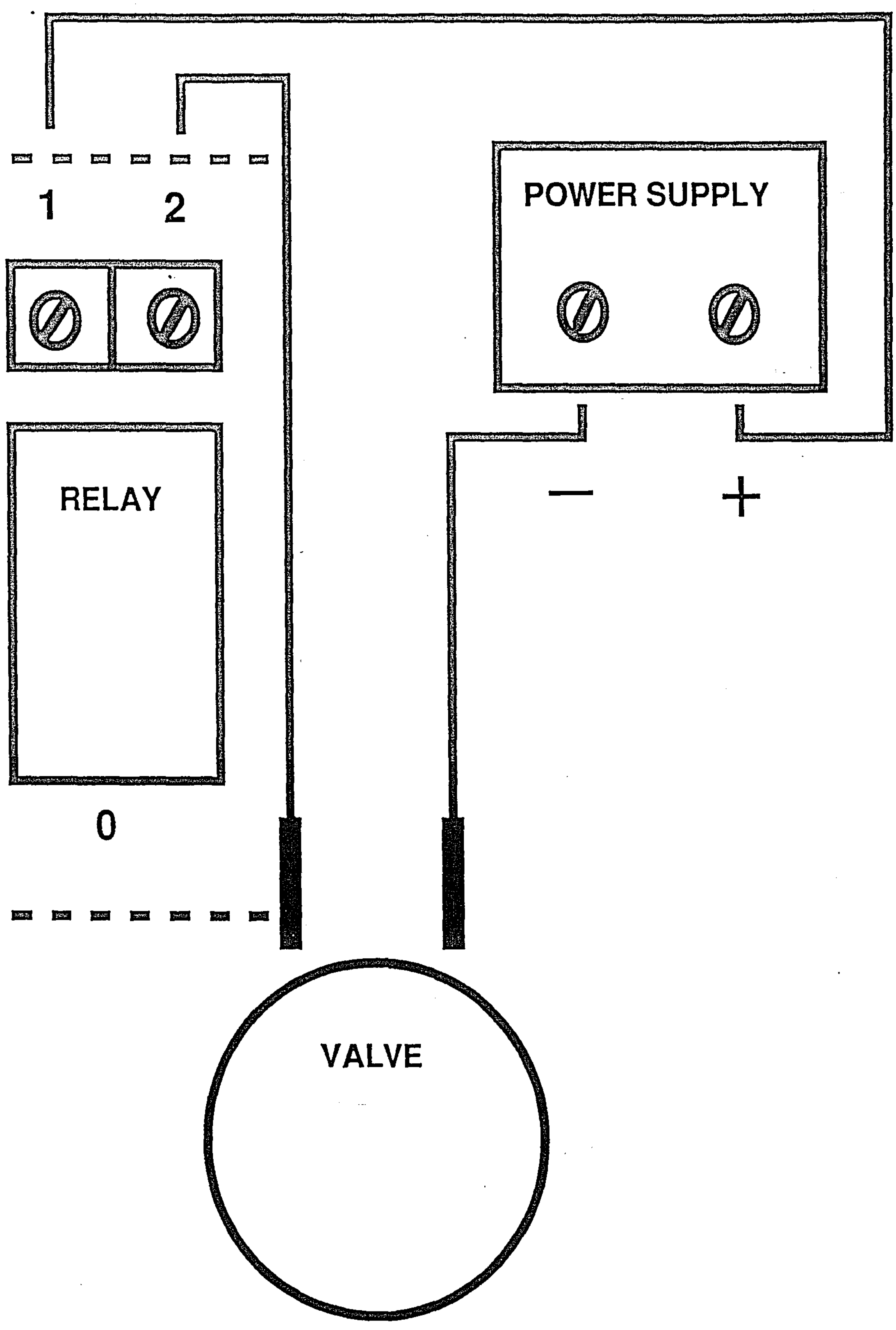


Figure 2-4: Interface Between Output of Robot Controller and Pneumatic Valve

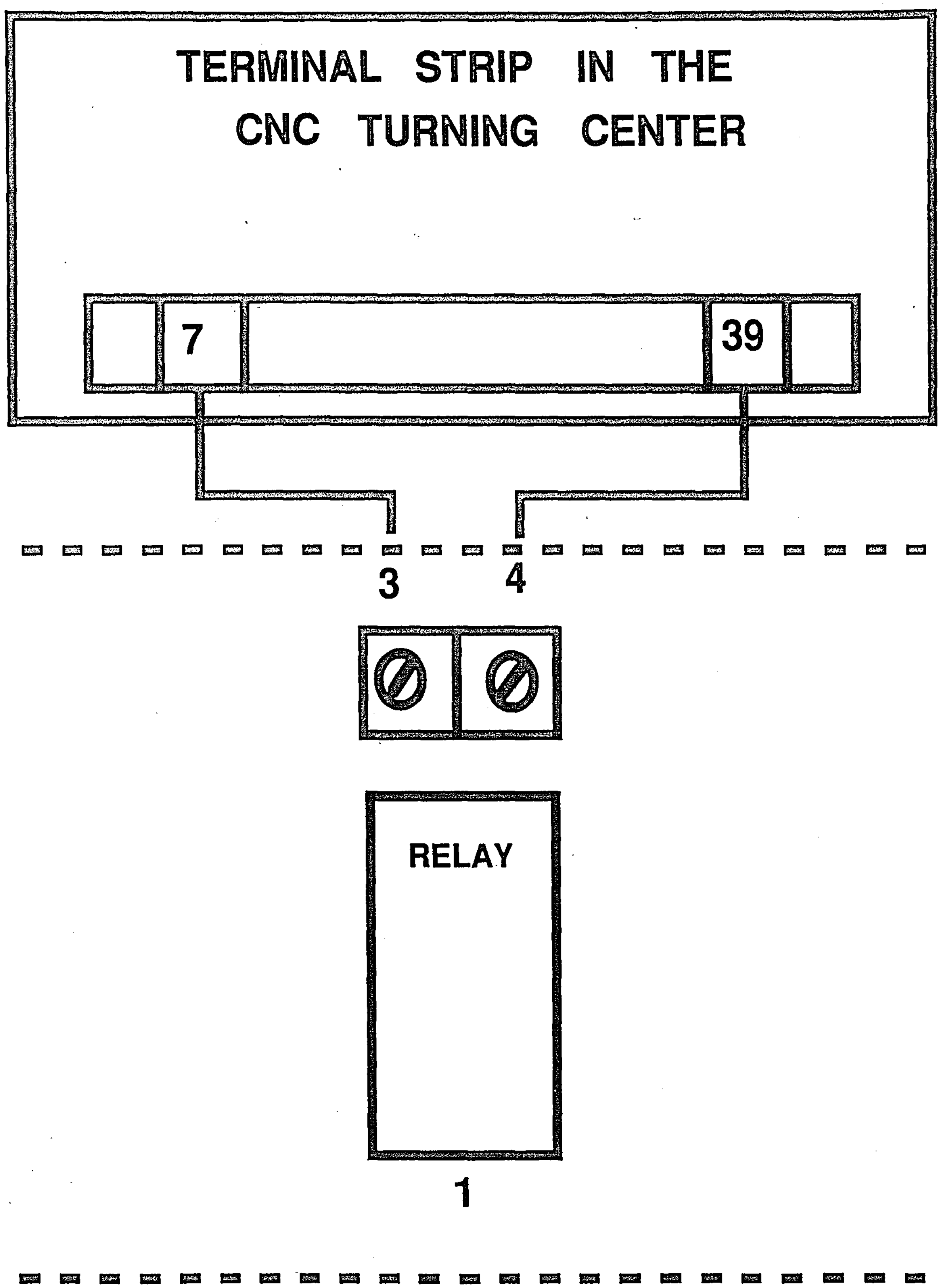


Figure 2-5: Interface Between Output of Robot Controller and Turning Center Start Cycle

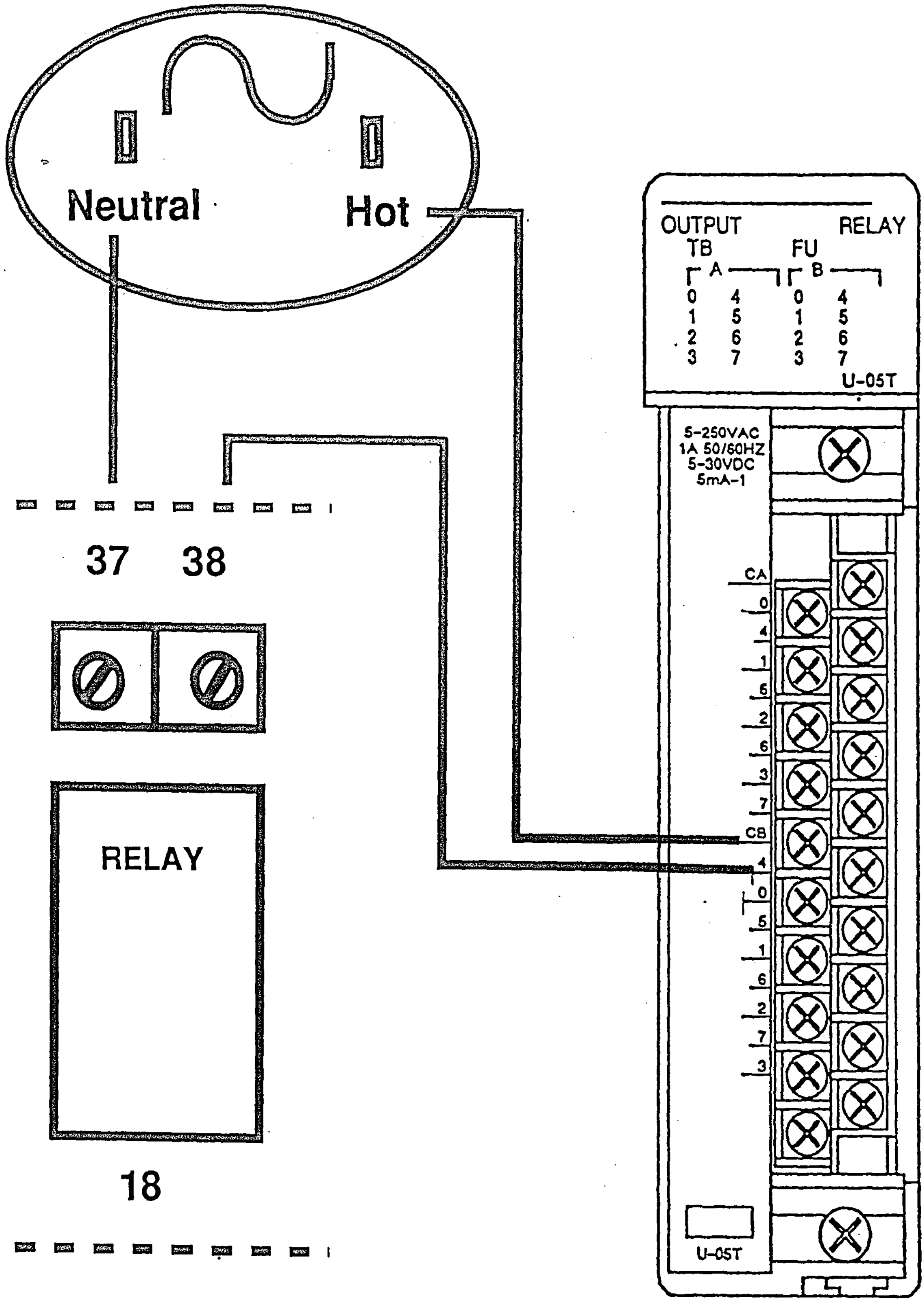


Figure 2-6: Interface Between Output of PLC and Input of Robot Controller

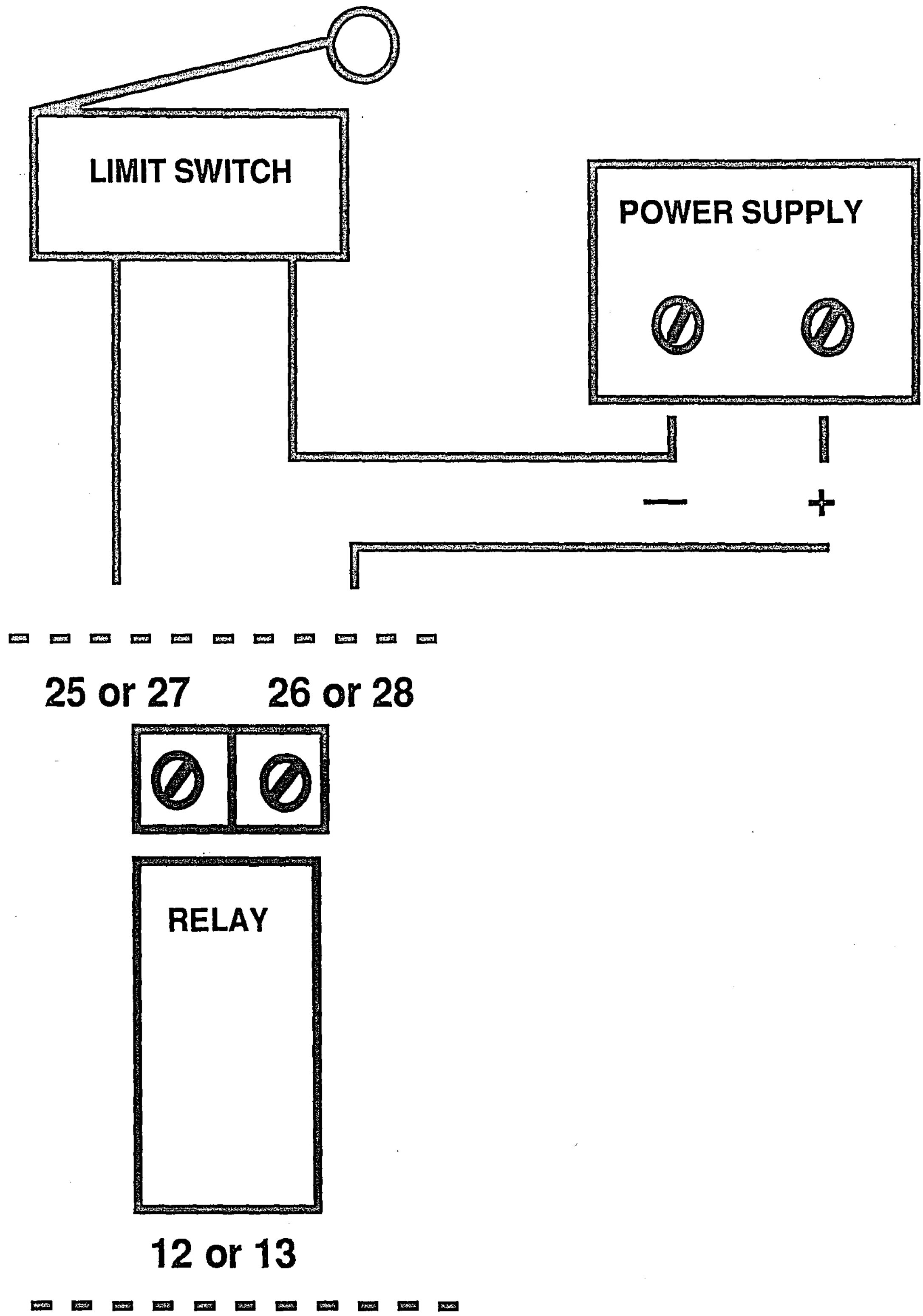


Figure 2-7: Interface Between Limit Switch and Input of Robot Controller

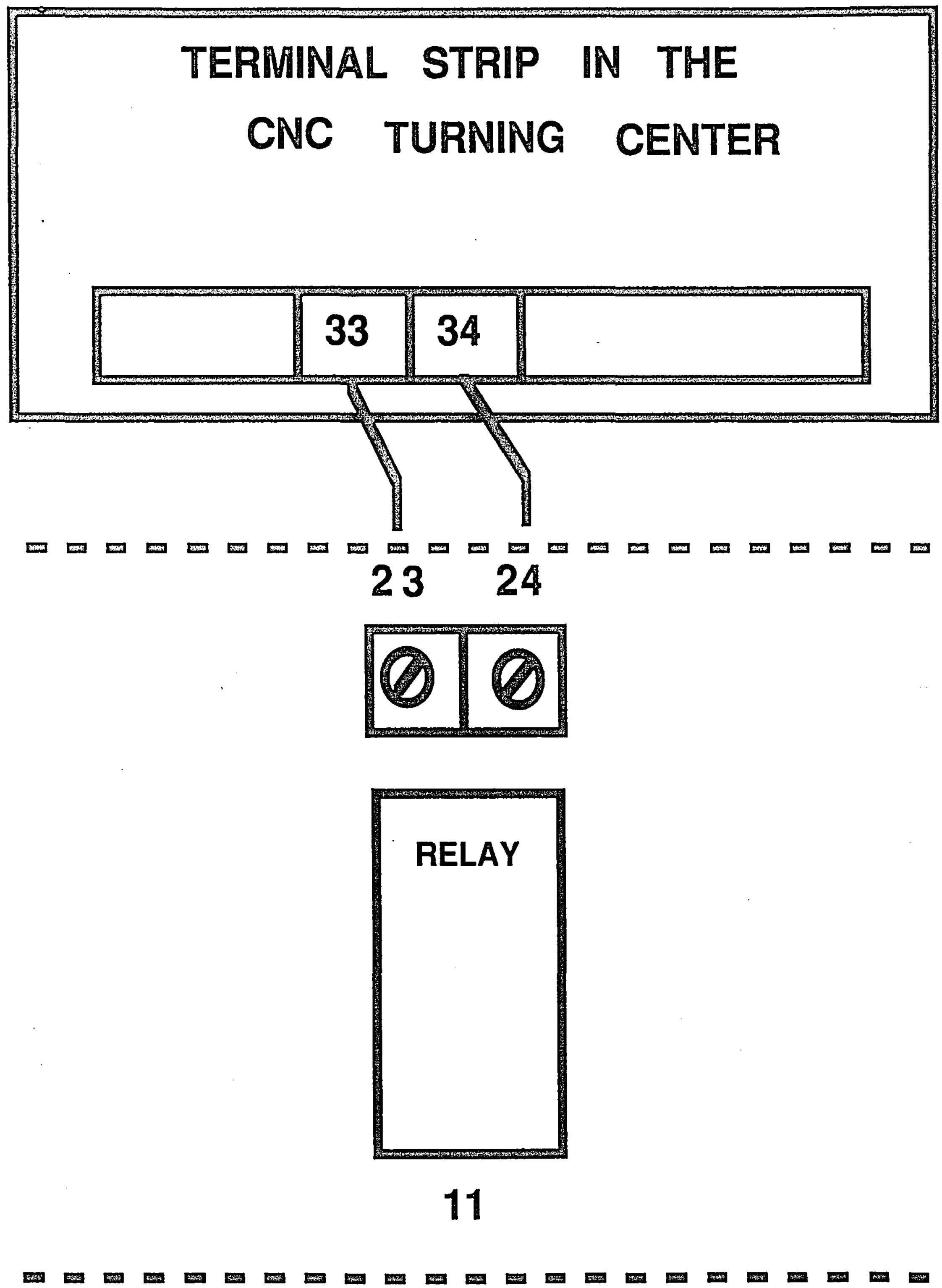


Figure 2-8: Interface Between Valve that Controls Collet and Input of Robot Controller

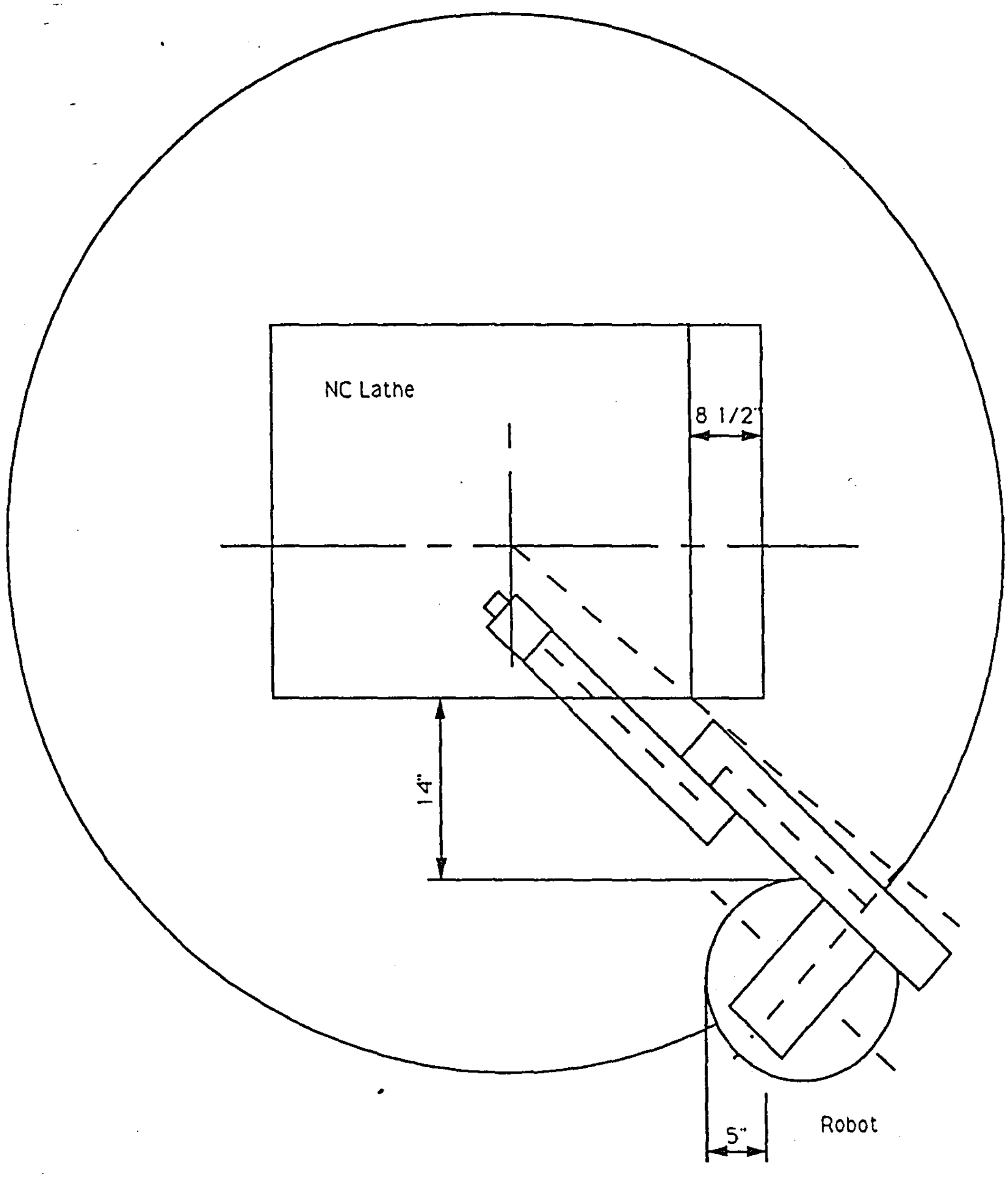


Figure 2-9: Relative Position Between Robot and CNC Turning Center

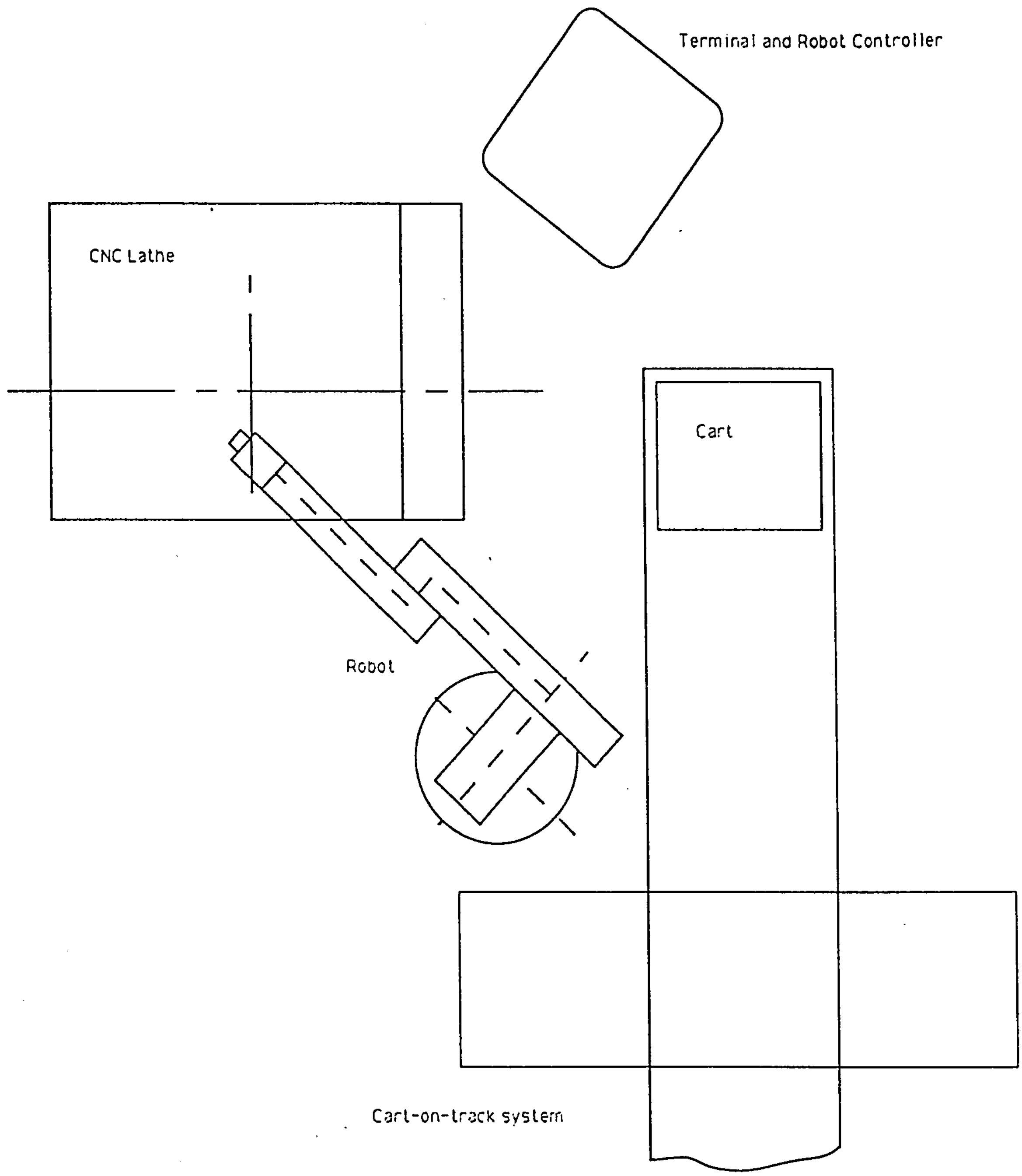
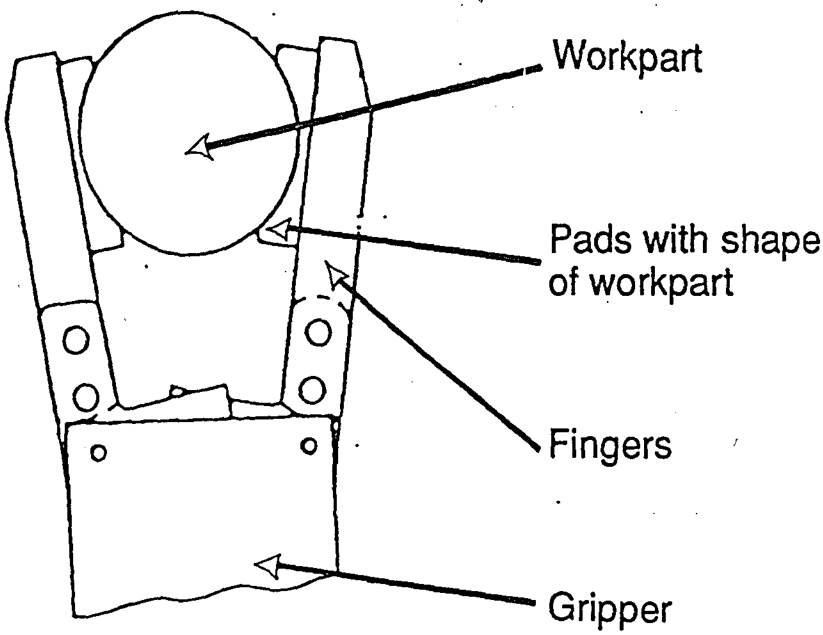
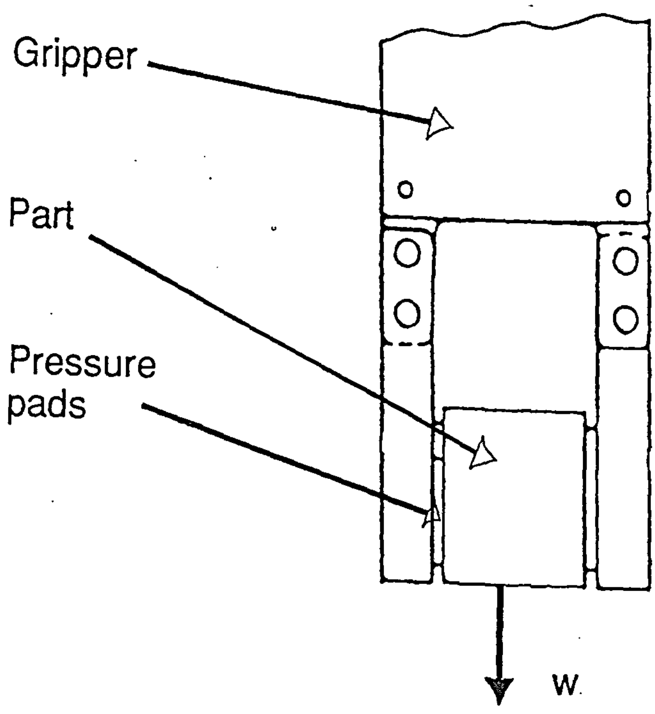


Figure 2-10: Cell Layout

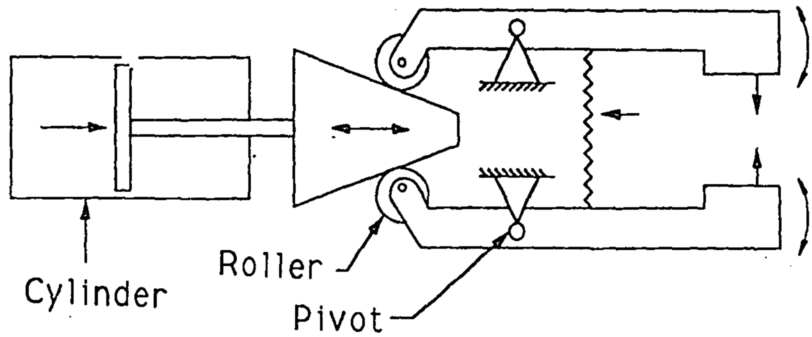


(a) Physical Constriction Method

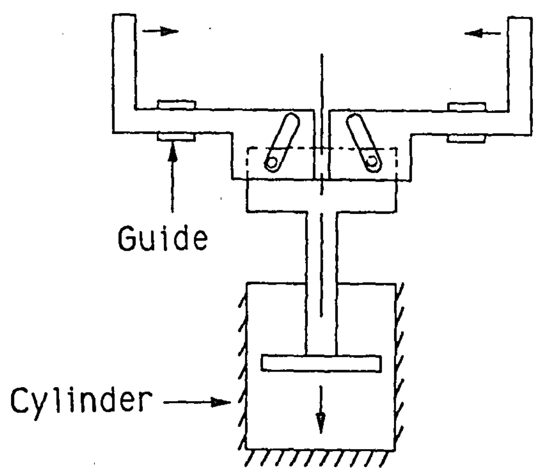


(b) Friction Between Fingers and Part

Figure 2-11: Methods to Constrain the Part in the Gripper
(from Groover, Weiss, Nagel, and Odrey, 1986)



(a) Pivoting



(b) Linear

Figure 2-12: Mechanical Gripper Finger Movements (from Hoshizaki and Bopp, 1990)

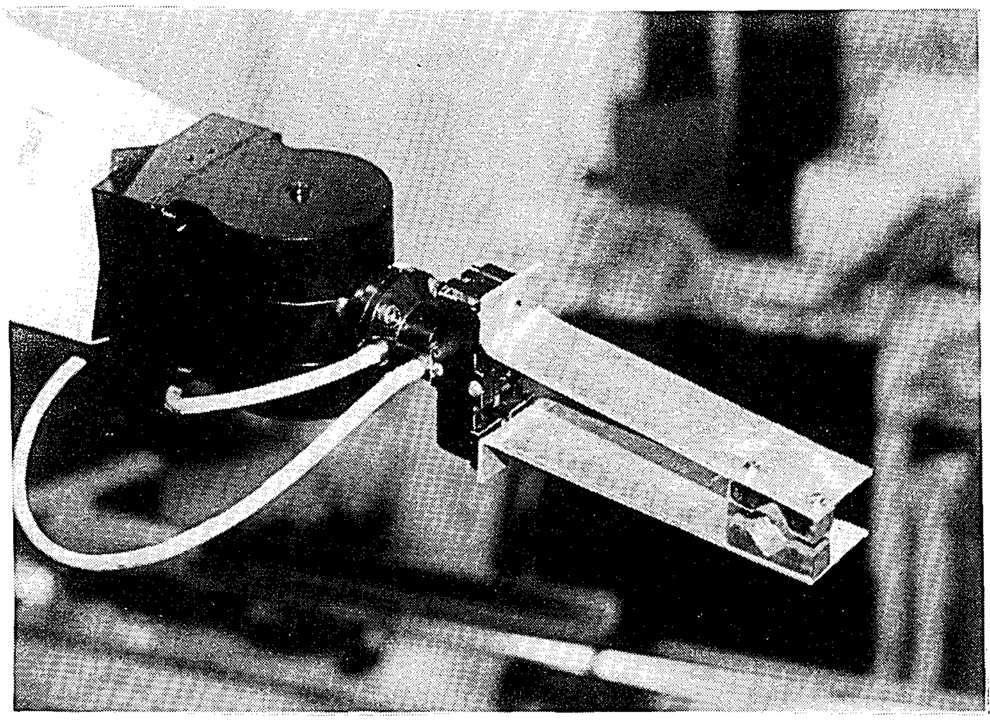


Figure 2-13: Gripper Prototype

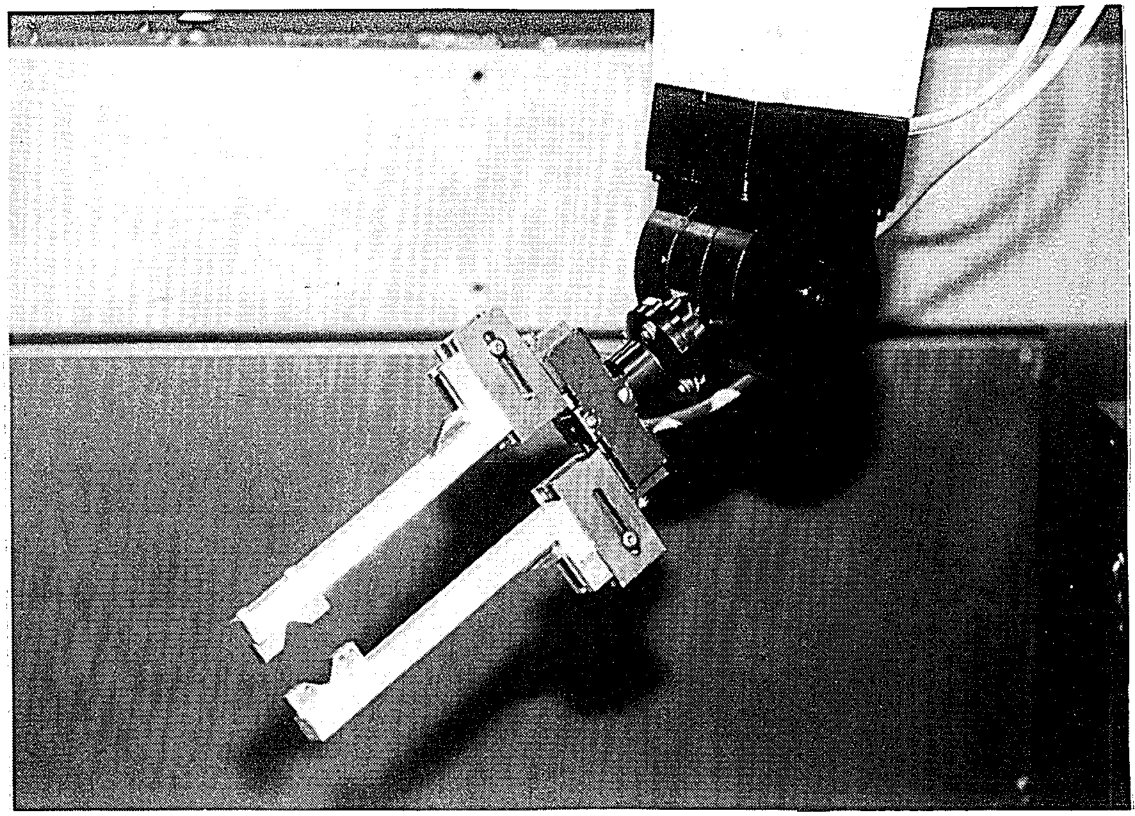


Figure 2-14: Final Gripper

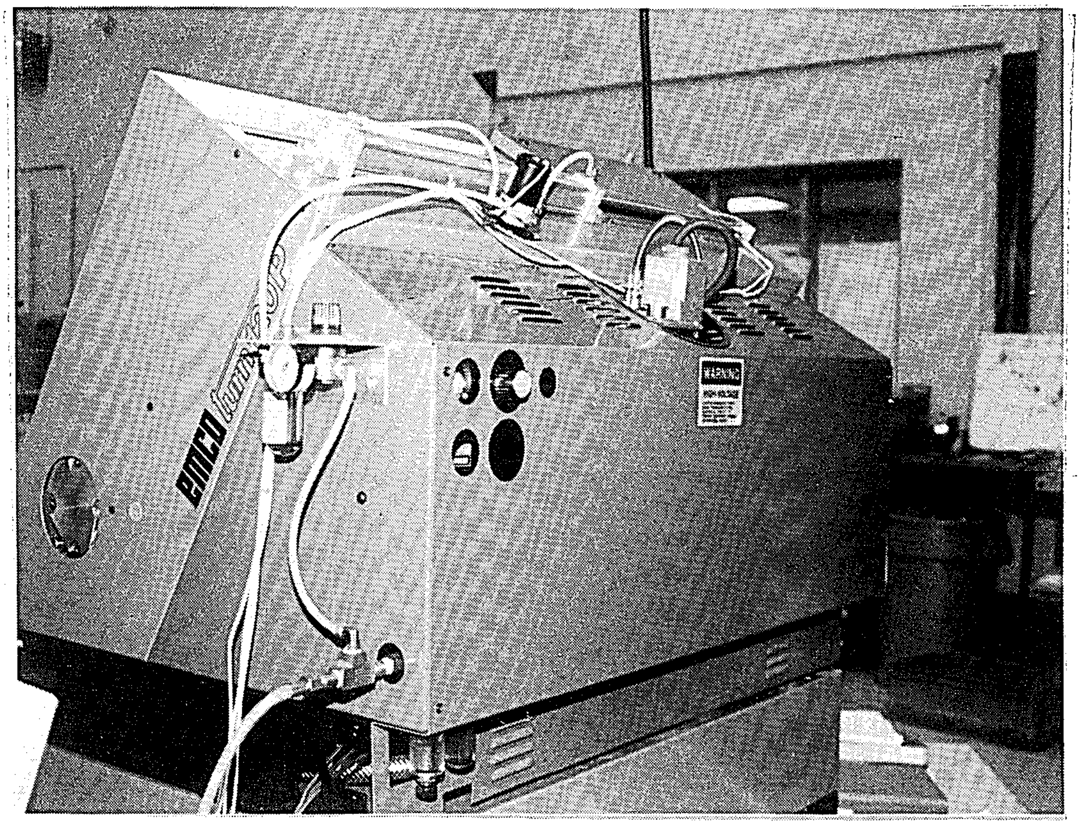


Figure 2-15: Pneumatic System

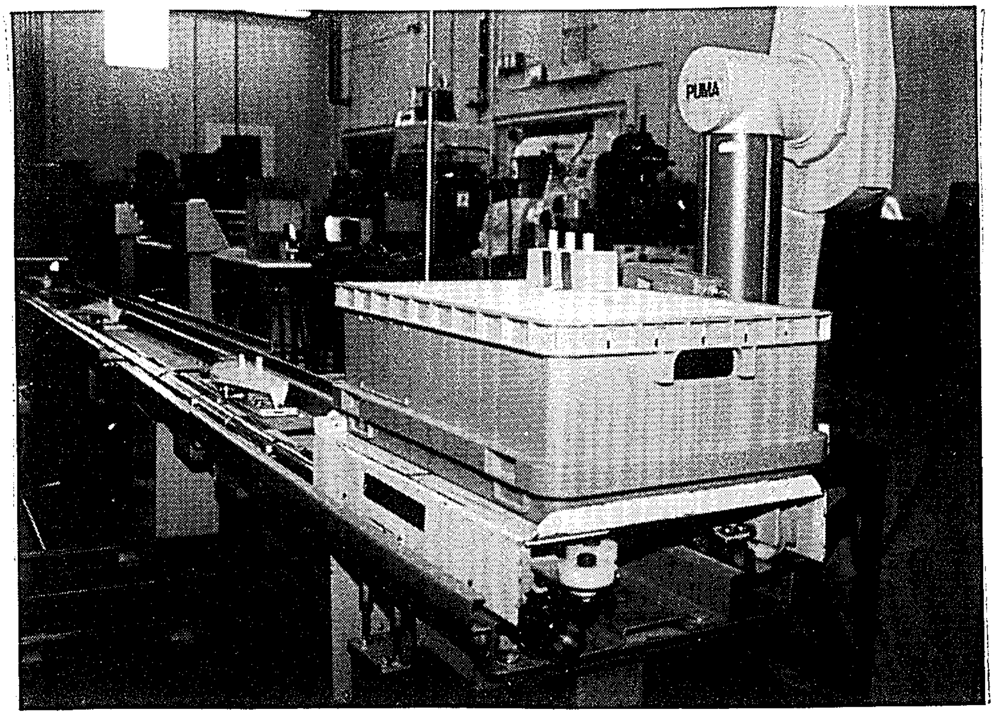


Figure 2-16: Pallet

CHAPTER 3

APPLICATIONS FOR THE CELL

This cell was not designed to work as a production workstation in a manufacturing plant. The purpose of this FMC is to be a valuable teaching tool for students. Students can profit from this resource in various ways in order to improve their knowledge in the field of FMC and FMS.

The first manner in which this cell could serve as a teaching tool is by demonstrating how the cell operates. In this way, students can gain an understanding of the way the cell components work together and of the interfacing between them. They can learn how to setup a CNC turning center, edit a NC program and prepare it to run automatically. They will also learn the basics of the robot arm, how to edit a VAL program in the robot controller and how to start the execution of that program. The cart-on-track system is not an important component of the cell, but preparing a program for the PLC to send a cart full of workpieces to the cell station could also be part of a laboratory assignment. A handout describing the various parts that make up the assignment would need to be prepared. Since it is probable that the student would only have a limited amount of time, he or she snould not be expected to master all the components of the cell. Thus, the handout should contain in some parts, steps that the student can follow without the need to study the subject in depth.

Another possible way to profit from this cell is by usuig a simulation program that would describe the cell and the actions inside of it. The cell would be represented on the computer by the main components and their relative positions. The operations that each component executes could be simulated by the software. It would be possible with this kind of simulation to analyze the operations and test different solutions. For instance, it would be possible to playback the trajectory of the robot arm and change it in order to optimize the cycle time of the cell.

If the simulation program also permitted the use of off-line programming, a student could generate a program to control the cell after optimizing the cycle time and then download it to the robot controller to test it.

The last way the FMC could be used is to integrate it in a FMS. The cell was built as part of a more complex system that includes a cart-on-track conveyor system and an AS/RS. The addition of other workstations in this system would be a step forward in the construction of a FMS. The ultimate step would be to create a central control system that would manage the operations of the whole system. This controller could be a computer connected to each part of the FMS, including the cell.

The construction of this system would demonstrate to the students the basic principles of a FMS. They would be able to realize and solve the problems encountered within such a system. An example of a problem that could be studied would be the scheduling and distribution of workpieces between stations.

CHAPTER 4

CONCLUSIONS

4.1 Summary

This project began with the goal of creating a flexible manufacturing cell by interfacing some elements already available at the Manufacturing Technology Laboratory at Lehigh University. The main elements available were: a CNC turning center, a jointed-arm robot, and a cart-on-track conveyor system. The goal was to create a cell that had as a production machine the CNC turning center. The robot would automatically load the workpieces into the turning center. The cell would be positioned by a station of the cart-on-track system. A cart would then transport workpieces to that station where the robot would pick up a piece and load it into the CNC turning center for processing.

The work began with a design of the layout of the cell. Because there was still the need to use the CNC turning center independently of the cell, enough space had to be provided in front of the machine so that a person could have access to the main parts of the machine. In the layout the robot was positioned in front and to the right corner of the turning center. In this way, space in front of the main spindle and controller of the turning center was available.

After being positioned, each main component of the cell (the robot, the CNC turning center and the cart-on-track system) had to be modified in order for it to function in the cell. The robot had to have attached to its wrist an end effector that would permit it to grasp the individual workpieces. A pneumatic gripper was constructed and attached to the wrist of the robot arm.

Two things had to be modified on the CNC turning center. The front door of the CNC turning center must be closed in order for the spindle to turn. Initially this door only moved manually. In order to run a cell cycle without the need for human intervention a mechanism to automatically open and close the door had to be installed. The mechanism consisted of a pneumatic cylinder attached to the body of the machine, parallel to the door movement, and a pneumatic circuit to control the movement of the cylinder. The rod of the cylinder was attached to the door by an aluminum plate that is easily removed, allowing the door to be manually operated. The collet attached to the main spindle of the CNC turning center also had to be modified. In order to facilitate the insertion of a workpart into the collet by the robot arm, the diameter of the collet was enlarged and a chamfer was machined on it.

Finally, the pallet had to be designed so that it could be placed on a cart and could hold and transport the workpieces to the station where they are processed. The manner in which the workpieces were positioned allows the robot gripper to grasp them.

The last step in building the cell was to interface the components with the cell controller. The robot controller was chosen as the cell controller. An I/O module with input and output relays is attached to the robot controller to permit interfacing with other devices. The interface with the machine tool uses signals to monitor the status of the machine and the position of its front door, and to produce the start of the machine cycle and the movement of the door. The interface with the PLC that controls the cart-on-track system is used to notify the robot controller of the arrival of a cart at the cell station and to remove the cart when the cycle is finished. A VAL program was written to control the sequence of operations within the cell. Figure 4-1 shows a picture of this cell.

4.2 Future Research

There are various areas related to this cell on which future work can be developed. Testing the reliability of the cell should be a priority. The cell cycle should be executed under several conditions to test whether these factors would cause a malfunction of the cell. Having the robot arm move too quickly, for instance, could cause it to loose its repeatability.

An important area to work on is safety. The cell area should be isolated from the rest of the laboratory to keep people from getting close when the cell is functioning. A fence should be constructed around the cell with only a door to permit access to the cell. If the door is opened during a cycle of the cell an emergency stop of all elements within the cell should be incorporated. Also the cycle of the cell should be carefully analyzed to determine its reaction to any malfunction. The detection of a malfunction should automatically produce an emergency stop of all elements within the cell.

An interesting area for further work is production increases in the cell. This can be accomplished by using a double gripper attached to the wrist of the robot arm. A double gripper has two grasping mechanisms to independently hold two separate workparts. For this cell the unloading and loading of the turning center could be done in the same step. While the machine tool is working on a workpiece, the robot could move towards a new workpiece, grasp it and return. When the machine tool finishes its cycle, the robot would be in a position to unload the processed workpiece and immediately load a new workpiece. A considerable amount of time would be saved with this operation.

Improvements can be made on the system that opens and closes the turning center's door. An electrical circuit can be installed that would permit the turning center's door to be operated by pressing a button. This button would only work when the turning center is operating in the stand alone mode. That is, when a person is working manually with the machine tool, the door would open or close by pressing this button.

The last area envisioned to do more extensive work, deals with the flexibility of the cell. In its present state the cell has more potential to be flexible. In order to produce a different part the cell has to be stopped at the end of a cycle and reprogrammed to be able to execute the new operations. It would be necessary to design an interface between the CNC turning center controller and the cell controller to execute different NC programs from the cell controller. To do this, the program that produces the sequencing of operations within the cell would have to be modified. The interface between the robot controller and the PLC would also have to be modified. With this interface the robot controller can be informed about the kind of product that is to be processed when a cart full of workpieces arrives at the cell station. The program in the robot controller will then generate the sequence of operations that will manufacture the product, including the retrieval and commencement of the right NC program in the machine tool.

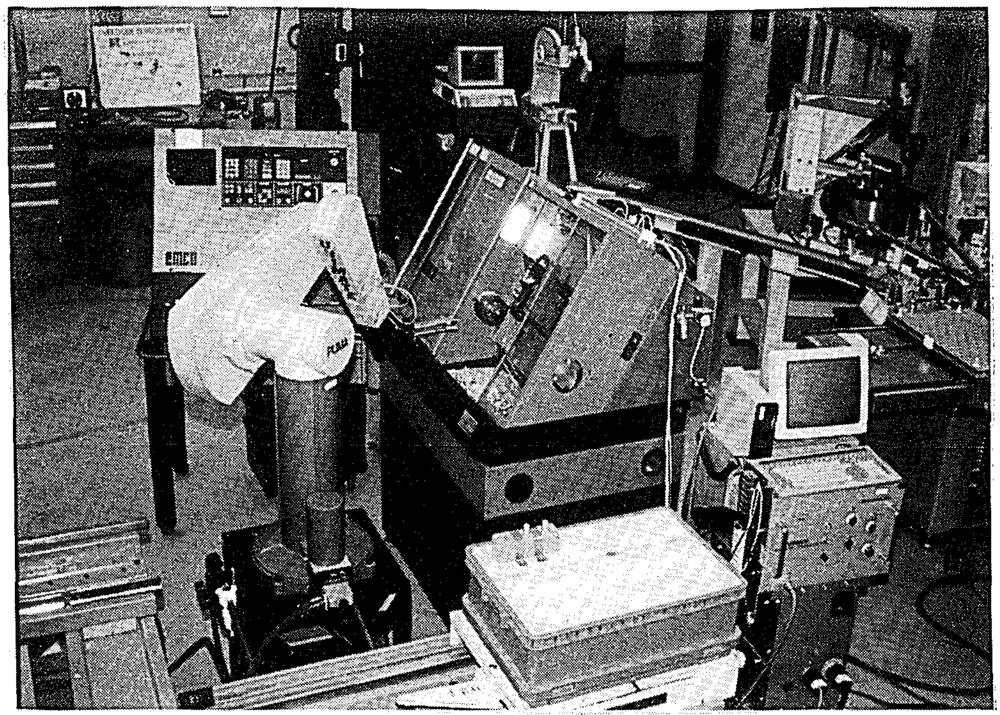


Figure 4-1: Cell

REFERENCES

Emco, CNC Turning Instruction Book. Emco Maier & Co, Austria, 1986.

Green, R. G., "Flexible Manufacturing Systems: Are they in your future?" Tooling Production, July 1986, pp. 35-38.

Groover, Mikell P., Automation, Production Systems, and Computer Integrated Manufacturing. Prentice-Hall Inc., Englewood Cliffs, New Jersey, 1987.

Groover, Mikell P.; Weiss, Mitchell; Nagel, Roger N.; Odrey, Nicholas G., Industrial Robotics - Technology, Programming, and Applications. McGraw-Hill Book company, New York, 1986.

Hoshizaki, Jon, and Bopp, Emily, Robot Apllications Design Manual. John Wiley & Sons, Inc., New York, 1990.

O'Grady, Peter, "Flexible Manufacturing Systems: Present Development and Trends," Computer in Industry, July 1989, pp. 241-251.

Puma Robot, 550/560 Series Equipment Manual - Volume I. Unimation Inc., 1982.

Talavage, Joseph, and Hannan, Roger G., Flexible Manufacturing Systems in Practice: Applications, Design and Simulation. Marcel Dekker Inc., New York, 1988.

Thomas, Rick, "Design Controls for Robotic Work cells," Industrial Engineering, May 1983, pp. 34-39.

Webb, John W., Programmable Logic Controllers - Principles and Applications. Macmillan Publishing Company, New York, 1992.

Young, C., and Greene A., Flexible Manufacturing Systems. American Management Association, New York, 1986.

APPENDIX

The following is the program that controls the workcell. It is called CELL. The signals of the I/O module used in the cell are specified by a number. The output signals are numbers 1, 2, and 8. The input signals are 1001, 1002, 1003, and 1008.

The trajectory followed by the robot arm is specified by the points recorded previously in the controller. The points used to specify the trajectory between the ready position of the robot arm and a workpiece in the pallet are called #POINT5 through #POINT1(a,b,or c). The points that specify the trajectory between the ready position of the robot arm and the collet of the CNC turning center are #POINT25 through #POINT20.

The program contains comments that facilitate better understanding.

```
        REMARK * Begin cycle when the signal from the PLC arrives *
5       WAIT SIG(1008)
        REMARK * Reset to initial state *
        RESET
        CLOSEI
        COUNT = 1
        REMARK * Open door and wait until door is open *
10      SIGNAL -1
        WAIT SIG(1003)
        REMARK * Move robot arm to grasp a workpiece from the pallet *
        SPEED 500 ALWAYS
        READY
        MOVE #POINT5
        MOVE #POINT4
        SPEED 25 ALWAYS
        REMARK * Decide which workpiece to grasp *
        IF COUNT = 2 GOTO 100
        IF COUNT = 3 GOTO 200
```

```
        REMARK * Move to grasp workpiece #1 *
        MOVES #POINT3A
        SPEED 10 ALWAYS
        MOVES #POINT2A
        MOVES #POINT1A
        DELAY 1
        OPENI
        MOVES #POINT2A
        MOVES #POINT3A
        COUNT = 2
        GOTO 300
        REMARK * Move to grasp workpiece #2 *
100     MOVES #POINT3B
        SPEED 10 ALWAYS
        MOVES #POINT2B
        MOVES #POINT1B
        DELAY 1
        OPENI
        MOVES #POINT2B
        MOVES #POINT3B
        COUNT = 3
        GOTO 300
        REMARK * Move to grasp workpiece #3 *
200     MOVES #POINT3C
        SPEED 10 ALWAYS
        MOVES #POINT2C
        MOVES #POINT1C
        DELAY 1
        OPENI
        MOVES #POINT2C
        MOVES #POINT3C
        COUNT = 4
        REMARK * Return to the ready position after having grasped workpiece *
300     SPEED 500 ALWAYS
        MOVES #POINT4
        MOVES #POINT5
        READY
        REMARK * Move to deposit the workpiece in the lathe's collet *
        MOVE #POINT25
        MOVE #POINT24
        MOVES #POINT23
        SPEED 25 ALWAYS
```

```
MOVES #POINT22
SPEED 10 ALWAYS
MOVES #POINT21
SPEED 5 ALWAYS
DELAY 2
MOVES #POINT20
CLOSEI
DELAY 1
REMARK * Move back to the ready position *
MOVES #POINT20A
MOVES #POINT21A
SPEED 10
MOVES #POINT22
SPEED 25
MOVES #POINT23
SPEED 500 ALWAYS
MOVES #POINT24
MOVES #POINT25
READY
DELAY 1
REMARK * Close the turning center's door, wait for signal that indicates a
         closed door and start the turning cycle
SIGNAL 1
WAIT SIG(-1002)
SIGNAL 2
DELAY 0.5
SIGNAL -2
REMARK * Wait for signal indicating that the turning center's cycle is
         finished, open the door and wait for signal that indicates an open
         door *
WAIT SIG(-1001)
WAIT SIG(1001)
DELAY 1
SIGNAL -1
WAIT SIG(1003)
REMARK * Move the robot arm to grasp part at the collet, drop part into a
         bucket, and return to ready position *
MOVE #POINT17
SPEED 25 ALWAYS
MOVES #POINT16
SPEED 10 ALWAYS
MOVES #POINT15
```

```
OPENI
MOVES #POINT16
SPEED 25 ALWAYS
MOVES #POINT17
CLOSEI
SPEED 500 ALWAYS
READY
REMARK * Decide if cycle should continue *
IF COUNT < > 4 GOTO 10
REMARK * Send signal to the PLC and begin again *
SIGNAL 8
DELAY 0.5
SIGNAL -8
GOTO 5
```

VITA

João Paulo Moreira Gonçalves is son of Domingos Gonçalves de Sousa and Maria Celeste Moreira da Silva Gonçalves. He was born in Muro - Quintão, Santo Tirso, Portugal, on January 31, 1968. He completed high school at Escola Secundária Rodrigues de Freitas in Porto, Portugal and immediately entered the Faculdade de Engenharia da Universidade do Porto. He completed a *licenciatura* in Mechanical Engineering in July, 1990. The last year of those studies was passed in France, where he trained at Renault Automobiles, Paris, and did course-work at Université de Technologie de Compiègne. These studies were funded through a grant of Renault Automobiles.

Mr. Gonçalves was granted a scholarship from Junta Nacional de Investigação científica e Tecnológica, in Portugal, to pursue a master of science degree in Manufacturing Systems Engineering at Lehigh University which began in January 1991. This scholarship was part of the AMNIOP program between several portuguese organizations and Lehigh University. He completed all course-work requirements for the degree in December, 1991.

END OF TITLE